

REDUCING MATERIAL COSTS
OF DRY COOLING TOWERS

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by

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ABSTRACT

Title of Thesis: Reducing Material Costs of Dry Cooling Towers

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This work describes some of the various engineering problems involved in using present materials technology to provide inexpensive heat exchanger surfaces in applications such as dry cooling towers used for waste heat disposal from power plants.

Characteristics of presently available plastics and filler materials are evaluated. Use of glass fiber reinforced plastics and glass materials is also discussed.

A previously developed computer program was modified to provide comparisons with previous computer optimized heat exchanger designs and cost evaluations.

Polyvinyl chloride and polycarbonate resins are selected as the best thermoplastic materials due to their temperature resistance and other characteristics.

Glass fiber reinforced plastics are found to lack long term resistance to hot water and cyclic stresses.

Glasses are found to be suitable from a thermal conductivity aspect, but to have several design problems.

The computer program analysis shows that non-metallic bare-tubed heat exchanger surfaces are competitive in capital cost with finned tube and packed bed surfaces, but somewhat higher in annual operations cost for forced draft cooling towers.

Natural draft towers are proposed to be the logical place to use non-metallic materials.

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I. Introduction

Generation of large quantities of electric power is usually accomplished either by hydro-electric means or, more frequently, by the use of stream driven turbines. Waste heat disposal from the condensers of these turbines is accomplished in various ways, each method having its own characteristic environmental, cost, and engineering problems.

For instance, the cheapest and least complicated mode of waste heat disposal is the single-pass tube-and-shell condenser which utilizes available natural water resources for cooling. Recently, these installations have been strongly opposed by environmentalists on grounds of the adverse effects of "thermal pollution" of natural bodies of water.

Since it is not desirable to locate all power plants on either a river, a lake, or the ocean, many installations utilize the evaporative (wet) cooling tower heat rejection system. This type of installation requires more capital investment but is used by many power plants. Excessive make-up water is required, however, due to rapid evaporation from the cooling tower, and the resultant fog plume may also cause concern from the environmental viewpoint.

Another alternative has long been recognized, that of using dry-cooling towers. However, their relatively high cost has precluded their use except in situations where there is no alternative.

The conventional concept of a dry cooling tower is best illustrated by referring to reference (1), which describes a tower built in 1962 at Rugeley, England, for a 120 megawatt power plant. This relatively small cooling tower installation uses a natural draft hyperbolic tower 350 feet high and 325 feet in diameter at the base. It incorporates 648 finned cooler sections arranged in 216 panels, each three sections high.

Dry cooling towers do not have to be made of high thermal conductivity (metallic) materials since the resistance to heat flow is usually much greater at the surface on the air side. Relatively low thermal conductivity can be tolerated within the material itself.

For example, although finned heat exchangers may be made with aluminum (thermal conductivity about 130 BTU/Hr.-Ft.-F), the overall coefficient of thermal conductivity (U) is only about 12 BTU/Hr.-Ft.²-F according to data in reference (2). This low thermal conductivity results not only from the fact that a solid-to-gas interface is present, but also from the effects of excessive laminar flow at that interface resulting from the closely spaced fins.

Thus, it may not be surprising that heat exchangers without fins and made of a material such as glass-fiber reinforced plastic (thermal conductivity about 0.2 BTU/Hr.-Ft.-F), using thin walled tubing (.030 inch), have a resultant U of about the same magnitude as finned heat exchangers made

from aluminum. (For detailed data see Chapter VII.) The advantage of using fins, of course, is the increased heat exchange area per foot of tube.

As part of an on-going dry-cooling tower research effort by the M.I.T. Heat Transfer Laboratory, the purpose of this thesis is to carry out the investigation of various materials which may be suitable as heat exchanger mediums in dry-cooling towers. Various design efforts in this area have established the need for inexpensive heat transfer mediums.

For example, the report by the M.I.T. School of Engineering Power Systems Engineering Group (3) recommended research efforts to attempt to reduce cooling tower capital costs by using alternate materials for heat exchanger surfaces. One of the figures of merit used in that report was inversely proportional to the total cost of the heat transfer surface required for the cooling tower. Thus, the requirement was that the net effects of cost and heat transfer effectiveness be traded-off as necessary to obtain a less expensive dry-cooling tower for a given power plant.

For comparison purposes, aluminum tubing (1"ID) costs about 30¢ per foot, fiberglass tubes cost about \$1.00 per foot and ordinary glass tubing is only about \$0.02 per foot.

Reference (2) describes relatively extensive work at M.I.T. on dry cooling towers and covers the less widely used concepts of periodic heat exchangers and packed bed heat exchangers. A computer program for analyzing the

relative costs of conventional finned tube heat exchangers is also given. This computer program was modified and used to analyze data on low thermal conductivity materials in this paper. (See Chapter VII.)

Neither reference (2) nor reference (3) attempted to find presently available, inexpensive materials for use in conventional dry cooling towers. It is this area which this paper proposes to cover in as much detail as possible, while at the same time presenting only relevant data and design information taken from the literature or produced in the M.I.T. Heat Transfer Laboratory.

II. Design Criteria for Material Selection

As already stated, the purpose of this research is to reduce the cost of building dry cooling towers. This means not only inexpensive base materials, but also easy assembly, minimum maintenance, and long life. Only when the relative economics of various total designs are compared on a life-cycle economic basis can it be predicted that one material will be more desirable than all others.

Unfortunately actual life-cycle data is unavailable in most comparison studies such as this, and many variables must be considered simultaneously in order to provide useful information as a general design guide.

Thus, the approach of this paper is to utilize an existing computer program (with minor adjustments) to evaluate the basic data generated with regard to various materials.

Although cost is the most important general figure of merit, it is not the only critical consideration. Since the ultimate objective of this work is to produce a cooling tower of relatively large size, other constraints are involved. This chapter will attempt to present additional relevant design factors such as flammability, service life, and chemical compatibility.

A. Flammability

References (4) and (5) detail the complex area of polymeric combustion. Of particular concern are the following points:

(1) The external heat source may introduce free-radical species that may affect or cause additional chain branching reactions that may alter the physical properties of material in the vicinity of a fire but not close enough to melt or be consumed. This is referred to as non-flaming degradation.

(2) An initially slow burning polymer fire may become a very rapidly spreading fire as a result of its high heat of reaction, generation of its own catalyst, or the production of gaseous or condensed reactants which may further react with oxygen after leaving the initial scene of combustion.

(3) Large quantities of smoke may be generated and polymer fragments may be dispersed over a wide area and generate clean-up problems in the surrounding community.

(4) Combustible as well as toxic gases may be liberated in large quantities and liquified materials may continue to burn such that the fire must be treated as a petroleum fire.

(5) Some polymers are "self-extinguishing" due to the flame front melting away. If the plastic is impregnated with a "wicking" material (even asbestos or metals), the composite material may be flammable.

(6) A fire would be a much more serious problem during construction and maintenance than during normal plant operation due to presence of water on the inside of the pipes during normal operation. The thin walled, high

heat transfer area heat exchangers envisioned in dry cooling towers could aggravate the flame propagation problem.

Thus, it can be seen that the flammability problem constitutes a significant body of engineering consideration when polymeric materials are being considered. Nevertheless, additional attention in this area is necessary if one is to realize all the possible complications involved. For instance, flame retardants may be added to polymers to decrease their burning rates. Halogens such as bromine and chlorine are used since the release of their gases during a fire helps to smother the flame.

Chlorine, however, when used in a flame retardant additive, may form strong acids during a fire or at elevated temperatures. Obviously, this could shorten the life of the "unaffected" heat exchanger surface dramatically.

Another source of possible trouble directly attributable to chlorine based fire retardants in the proposed application in dry cooling towers depends more upon the total system characteristics. Low molecular weight fire retardants will separate (sublimate) out of the plastic, especially at elevated temperatures expected in a dry cooling tower. If the system design includes a direct mixing condenser (and it most likely will), free chloride ions may reach the boiler or steam generator. If, as in some nuclear power plants, stainless steel components are present at high stress and temperature, any free chloride ions present would lead to chloride stress corrosion and accelerated component failure.

These considerations are pointed out merely to alert the reader to the possible serious consequences of ignoring the need to study each system individually, in detail, rather than accepting general specification such as "self-extinguishing". The complete technology of polymer flame retardance is significantly more complex than is presented here.

Reference (5) provides a description of materials and their toxic products of combustion. To underscore the need for obtaining a proper perspective on the flammability of various materials, this information is provided in Table I. Also, it should be noted that although halogens are useful in reducing the burning rate of polymers, during combustion the halogens are usually released as the hydrogen halide. These gases are more toxic than carbon monoxide.

From the above discussion, it is easily concluded that one would much prefer non-flammable (or at least self-extinguishing) materials in our cooling tower, assuming that they could be obtained with a minimum of additional cost. Also, fire retardant and other additives must be investigated in detail from a chemical engineering and corrosion viewpoint. Only then can it be assured that the total power plant design incorporates compatible materials. Thus, no recommendations (other than the above comments) for such additives can be made here.

B. Costs

Turning now to another design criteria, that of

TABLE I
TOXIC PRODUCTS THAT MAY BE OBTAINED
FROM COMBUSTIBLE MATERIALS

| TOXIC GAS OR VAPOR | SOURCE MATERIALS |
|-------------------------------------|---|
| Carbon Dioxide Carbon Monoxide | All combustible materials containing carbon |
| Nitrogen Oxides Hydrogen Cyanide | Celluloid, polyurethanes Wool, silk, plastics containing nitrogen |
| Formic Acid Acetic Acid | Cellulosic materials, Cellulosic plastics, rayon |
| Acrolein | Wood, paper |
| Sulphur Dioxide | Rubber, thiokols |
| Halogen Acids Phosgens etc. | Polyvinyl chloride, fire-retardant plastics, fluorinated plastics |
| Ammonia | Melamine, nylon, ureaformaldehyde resins |
| Aldehydes | Phenol-formaldehyde, wood, nylon, polyester resins |
| Benzene | Polystyrene |
| Phenol | Phenol-formaldehyde |
| Azo-Bis-Succino Nitrile | Foamed plastics |

inexpensive construction and maintenance, one may make several preliminary points. For example, ease of fabrication depends on several rather obvious factors such as weight, machinability, joining method complexity, support requirements, and susceptibility to damage. Comparing various materials in these areas is much more difficult than comparing easily identifiable quantities such as cost and flammability.

The non-metallic materials may produce savings not only by reducing material costs, but also by enhancing pre-assembly and transportation advantages. Net capital costs may be compared using the computer program of reference (2), as modified in this paper. The original program designs heat exchanger modules, given the basic geometry of the tubes and fins or the packed bed characteristics. It integrates this module into the entire power plant and optimizes the design such that minimum costs are achieved.

That program utilizes a polynomial expression to relate capital costs of dry cooling towers to "bare-tube" surface area of the finned heat exchanger elements. The coefficients of the polynomial are inputs to the program and can, thus, be modified by a constant factor which reflects the expected savings of any particular design due to the special features of that design.

By way of illustration, the chemical industry already uses PYREX[®] glass heat exchangers of relatively

expensive design. If the design constraints of these heat exchangers are modified to reflect cooling tower requirements, a qualitative argument may be developed to show that, although "bare-tube" heat exchanger surfaces require more tubes, a somewhat modest "cost factor" may be reached such that the capital costs of bare-tubed heat exchangers are competitive.

For example, the capital costs of metallic heat exchangers (finned) are about \$11/Ft.² of bare-tube surface. This happens to be about the same price as the (high-quality) chemical industry glass heat exchangers. Based on the computer analysis (Chapter VII.), a cost factor of 0.5 is required to obtain competitive capital costs. This would be a reasonable goal if inexpensive glass was used and if strength and leakage requirements were reduced.

Inexpensive glass could replace the PYREX[®], which costs about 6 times as much as the glass used in fluorescent lights. The only quality reduction of note here would be resistance to thermal shock. This is probably of minimum concern in this walled, low temperature range applications such as cooling towers, but may be vital in cold climates during plant start-ups.

If leakage requirements are reduced, it may be possible to avoid beading (flaring) the ends of the glass tubes and cheaper manifold connections devised.

Strength requirements may be reduced by prescribing vertical tubes instead of horizontal tubes. This would avoid

high tensile stresses and distribute the load more evenly. Thinner walls would result and the manifolds may be more accessible and less complicated in some designs. It also becomes possible (although obviously undesirable) to revert to an evaporative (wet) cooling tower condition at breakage locations.

With these considerations in mind, it would be quite simple to reach the capital cost factor of 0.5 described above. A complication enters, however, when vertical heat exchanger elements are proposed. It becomes more difficult to deal with the effects of wind on the flow of air into the tower. This is because vertical tubes must be arranged around the base of the tower, whereas horizontal tubes may be arranged inside the tower such that the air flows up through the heat exchanger rather than horizontally. This minimizes the effects of flow reversals at points located 90 degrees from the wind.

Capital costs present only part of the cost comparison, however. The fact that un-finned heat transfer surfaces require more bare-tube surface and, thus, larger heat exchangers, leads to an increase in air flow requirements. This additional air flow increases the annual operating costs of the fans.

A conclusion which may be reached here is that bare-tubed heat exchangers will show their maximum competitive strength in natural draft cooling towers. Since the computer program utilized here does not consider natural draft cooling towers, such interpretations as this must

remain qualitative in this paper.

C. Service Life

With regard to materials, qualitative analysis is reliable only if gross differences in overall performance are evident. Where such gross differences do not occur, final selection will usually be made in favor of those materials which present the least design uncertainty. Even in the case where there is a gross difference in relative qualitative worth of two materials, the design uncertainty associated with the "best" material may be significant enough to discourage its use.

For example, it is a simple matter to make a case for selecting glass reinforced plastic pipes over metal pipes in cooling tower applications until one considers the relatively unpredictable problem of degradation of the glass to plastic interface and the degradation of the plastic materials themselves in the hot-water environment. Also, thermal transients may produce severe interface fatigue cycles in composite materials due to differential thermal expansion. Thermal transients as well as water temperature are a function of individual plant design and operating requirements.

Thermoplastic materials are also subject to deterioration over long service lives due to their characteristically high creep rates. Long lengths (20 ft.) of thin walled (about .060 inch) small diameter (less than one inch) thermoplastic tubes would be subject to stresses which would lead

to gross elongation in a horizontal heat exchanger tube bank. Even the strongest thermoplastics have creep rates that are excessive. Reference (6) presents detailed creep and stress-strain results for an average strength thermoplastic, cellulose acetate, at 78F. At this temperature, the maximum tensile stress is about 6,000 psi. At a stress of only 1,690 psi, however, elongation is about 10% in 1000 hours. At 2,008 psi this becomes 30% in less than 500 hours. At 176F, this material has a maximum tensile strength of only 2,000 psi.

Thus, depending on specific design loads and temperatures, creep may become the limiting factor for thermoplastics. More subtle limitations may also appear. As previously stated, plastic materials are capable of contaminating the power plant with undesirable species such as chloride ions. Conversely, it must be recognized that some steam plant additives (such as morpholine, for example) which are designed to control steam plant chemistry (pH) and reduce corrosion of metallic components, may actually attack a polymeric heat transfer surface and cause it to fail. Such possibilities, once again, must be considered and examined in detail before committing capital resources to actual construction of a cooling tower.

Thermosetting materials (polyesters, epoxy, etc.) are characteristically more resistant to temperature, creep, and chemical attack and would, thus, eliminate thermoplastic materials from further consideration except for the fact that

thermoplastics are much easier to extrude than thermosets.

Glass materials are sensitive to surface flaws and, thus, over a period of time glass tubes would be weakened by impact from solid particles in the air stream. The glass tubes would need protection from dust storms, hail, and even vandals.

Further discussion of these various materials and their more detailed properties may not be necessary for the casual reader, however, the next few chapters consider the various alternative materials available: polymers, reinforced polymers, and glasses. Then a chapter is devoted to comparing these materials with each other and selecting those which may best meet our design criteria.

The thermal conductivities of various combinations of composite materials or of homogenous materials may then be incorporated into the modified computer program and the results analyzed. From this, specific future goals and recommendations may be made.

III. Polymers

The plastics industry is relatively new and is still developing at a rapid rate. New materials are being placed on the market each year and the possible combination of base resins and fillers is essentially infinite.

For the present purposes, however, many materials may be immediately eliminated due to their degradation at elevated temperature, their excessive flammability, or their relatively high cost. Others may be eliminated on the basis of their susceptibility to degradation by water.

A. Comparisons of Types of Polymers

Reference (7) defines this degradation as hydrolysis and describes it as a process where water attacks the polymeric linkage (characteristic of polymer materials) and produces carboxylic acid (-COOH) and hydroxyl (OH) groups. This process is sensitive to temperature and to the number of available bond sites along the polymer chain. Depending upon the particular material considered, these chemically functional terminal groups may be an advantage or a disadvantage, but in a finished product the effect of hydrolysis is usually a disadvantage.

Reference (8) provides a comprehensive source of information concerning the various polymer resins available and, since it provides some price information, it serves as a useful basis for comparison of the relative merits of the materials available on the market. Since it was printed in 1966, one must be aware of the limited value it will have

in providing absolute cost figures. It does show relative costs of all of the basic groups of polymers, however.

Pursuing the flammability criteria, one may find in Table II that the non-flammable materials are very expensive when compared with the self-extinguishing or slow burning resins available. The non-flammable materials will not support combustion at all, while the self-extinguishing materials will burn only in the presence of an external heat source. Slow burning materials may be defined arbitrarily as those with a flame front propagation rate of less than 0.5 inch per minute.

Also listed in Table II are some of the more common trade names of commercial resins whose principal constituent is the material listed. Note that some products have multiple variations (e.g., TEFLON[®]), and some products are identified only by the company name.

Cost per pound and estimated cost per square foot of outside heat transfer surface (based on 50% fabrication cost, 50% material cost) for 0.060 inch walled 1.0 inch inside diameter tubes are also found in Table II.

Thermosetting materials are generally self-extinguishing; however, it is convenient to include them as part of the discussion of glass-fiber reinforced plastics in Chapter V. Thus, Table II considers only thermoplastic materials. The principal difference between thermoplastic and thermosetting materials is that the molecules of the thermosets are cross linked to a much greater extent. This

makes thermosets less sensitive to the effects of temperature changes and also much more difficult to extrude.

Table II does not include many types of thermoplastics which are obviously inappropriate for use in cooling towers due to their decomposition at relatively low temperatures. Such materials are included in the next section, however, in order to clarify some of the material properties of thermoplastics.

B. Mechanical Properties of Polymers

Polymers are often anisotropic and, thus, many mechanical properties as well as thermal properties are directionally dependent. Thermal conductivity parallel to the polymeric chain in a unidirectionally oriented polymer will differ from that in the directions perpendicular to the chain. Thus, very misleading information can be generated if the test procedures do not take this phenomenon into account.

The addition of various fillers in wide ranges of combinations, particle sizes and relative amounts make it even more hazardous to attempt theoretical or even experimental analysis.

Mechanical properties depend not only on polymer orientation, but also upon the length of the molecular chain and the types and number of bonds. In general, the longer the molecular chain, the stronger the material. This length, however, is quite sensitive to the fabrication process used and the various additives involved which influence

TABLE II
RELATIVE COSTS OF THERMOPLASTIC MATERIALS⁽⁸⁾

NON-FLAMMABLE:

| | <u>COST/POUND</u> | <u>ESTIMATED*</u> <u>COST/FT²</u> |
|--|-------------------|---|
| Polytetrafluoroethylene (TEFLON) | \$ 3.25 | \$ 2.00 |
| Fluorinated polyethylene - co-propylene, FEB - resins (TEFLON) | 9.60 | 5.90 |

SELF-EXTINGUISHING:

| | | |
|---|-------|------|
| Polyvinyl Chloride, rigid (Exon, Geon, Dow, Marvinol, Vipla, Bakelite, Opalon, Escambia, Pliovic, Vyram) | 0.16 | 0.10 |
| Polyvinylidene chloride, rigid (Hi-Temp GEON) | 0.50 | 0.31 |
| Chlorinated polyether (PENTON) | 2.50 | 1.54 |
| Nylon 66 (ZYTEL, CATALIN) | 0.98 | 0.60 |
| Nylon 6 (FOSTA, SPENCER, PLASKON CATALIN, ZYTEL, FIRESTONE) | 0.92 | 0.57 |
| Polycarbonate (LEXAN, MERCON) | 1.175 | 0.72 |

SLOW-BURNING

| | | |
|---|-------|------|
| Polyethelene, high density (SUPER DYLAN, MARLEX, FORTIFLEX, PETROTHENE, HI-FAX, CATALIN, GREX, BAKELITE, TENITE, DOW, ALATHON, MONSANTO) | 0.265 | 0.17 |
|---|-------|------|

* Based on 50% fabrication costs and 50% material cost for 0.060 wall, 1" inside diameter tube, per airside surface areas.

TABLE II (cont.)

RELATIVE COSTS OF THERMOPLASTIC MATERIALS⁽⁸⁾SLOW-BURNING

| | <u>COST/POUND</u> | <u>ESTIMATED*</u> <u>COST/FT²</u> |
|--|-------------------|---|
| Polypropylene (MOPLEN, PROFAX, CATALIN, POLYPRO, ESCON, TENITE, AVISON, DOW, OLEMER, MARLEX) | \$ 0.30 | \$ 0.19 |
| Polyurethane (ESTANE, TEXIN, HI-TUFF) | 1.40 | 0.86 |
| Polychlorotrifluoroethylene (KEL-F, POLYFLUORON) | 6.50 | 4.00 |

*Based on 50% fabrication costs and 50% material cost for 0.060 wall, 1" inside diameter tube, per airside surface areas.

this length. Thus, valid experimental results can be quite dependent upon the process used, the machine used, the rate of production and cooling rates.

Also, it should be realized that even after a polymeric product is in place the associated loads may cause stretching of the polymer and change the degree of orientation of the polymer. Further, polymers are not perfectly elastic and are subject to "viscous creep". Thus, they are known as viscoelastic materials. Suitable tests as described in reference (9) must be employed to study creep, stress relaxation, stress-strain relations, and dynamic mechanical behavior.

To further complicate the above consideration, polymers exhibit property changes at certain transition temperatures. The most significant of these is the "glass-transition temperature", T_g .

Simply stated, the glass-transition temperature is the temperature below which a polymer behaves as a relatively rigid plastic and above which it behaves as a rubber. Physically, it may be considered as the temperature above which the cross-linkages of the polymer chain no longer prevent relative motion between molecules.

Thus, it is important that creep tests be carried out at a temperature at least as high as the maximum expected operating temperature for the cooling tower in order to ensure satisfactory design analysis. Selected polymers and their glass-transition temperatures are listed in Table III.

Plastics are softened by adding a liquid "plasticizer" which lowers the glass-transition temperature. Also, if two different monomer chains are combined to form a copolymer, the resultant glass-transition temperature will be somewhere between those of the pure monomer materials.

When expressed in degrees, Kelvin, the glass-transition temperature for crystalline polymers, is in the range of only 50 to 70 percent of the melting point, T_m , but may vary depending on crystallinity. The melting point of a polymer depends to a large extent upon the length of the molecular chain. The higher the molecular weight, the higher the melting temperature. Also, T_m may be lowered by the presence of solvents or plasticizers.

Many of the properties of plastics depend on the crystallinity. The crystalline structure depends on cooling rates from the melt condition, much the same as for metals. Since many manufacturing processes require thermoplastics to be heated to the melting point or above, the resultant products will have properties which may depend upon the machinery design, thicknesses involved and even atmospheric conditions.

If, while at a temperature above the glass-transition temperature, the material is stretched, the polymeric chain will become oriented in the direction of stretching. Upon cooling below the glass-transition temperature, the plastic will become anisotropic if the chains have not been allowed to return to their original shape.⁽⁶⁾

TABLE III
GLASS-TRANSITION TEMPERATURES
OF SELECTED POLYMERS⁽¹⁰⁾

| <u>POLYMER</u> | <u>T_g(°C)</u> | <u>T_g(°F)</u> |
|----------------------------------|--------------------------|--------------------------|
| POLYETHELENE | -120 | -184 |
| POLYPROPYLENE | -10, -18 | 14, -4 |
| POLYVINYL FLUORIDE | -20 | -8 |
| POLYVINYL CHLORIDE | 87 | 190 |
| POLYVINYLIDENE CHLORIDE | -17 | -1.4 |
| POLYCHLOROTRIFLUOROETHELENE | 45 | 113 |
| POLYTETRAFLUOROETHYLENE (TEFLON) | 126 | 259 |
| POLYVINYL ACETATE | 29 | 84 |
| CELLULOSE ACETATE | 120 | 248 |
| POLYCARBONATE (LEXAN) | 150 | 302 |

Thus, it may be easily concluded that if legitimate analysis of the relative merits of various polymer materials is to be obtained, one must be extremely conscious of the problems involved with obtaining reproducible samples. In other words, it is quite impractical to attempt to make samples in the laboratory (especially without extrusion equipment) and then accurately relate the samples to extruded, thin-walled pipe coming off a production line. Samples made in the laboratory can be expected to give "ball-park" values of some properties, however.

C. Characteristics of Selected Thermoplastics

Creep is a phenomenon which must be considered in every engineering design problem. Acceptable levels of creep in tube materials are determined by such factors as expected service life, effects on fluid flow, and aesthetics. Assuming that low creep rates are desirable, Table III may be used as a guide to select the most desirable thermoplastic from this viewpoint since creep resistant materials have high glass transition temperatures (T_g).

If the more expensive materials (such as TEFLON) are eliminated along with relatively flammable materials, the only remaining (high T_g) materials are polyvinyl chloride and polycarbonate.

If high creep rates are acceptable, the (very low cost) polyethylene and polypropylene resins should be added to the list. Thus, the list of possible materials has been reduced to four.

Table IV compares the relevant properties of these materials. It is quite impractical to attempt to select any one material from these four without knowing the precise constraints involved in a particular design. For example, the only advantage that polycarbonate has compared with rigid polyvinyl chloride is its higher T_g and thus better resistance to higher temperatures.

Some creep data was given in Chapter II for cellulose acetate since it is representative of the temperature resistant thermoplastics and the data was available for different loadings and temperatures. Again, stresses must be minimized in thermoplastic tubes by using adequate support if the tubes are to be horizontal.

Additional data on creep rates is available in reference (10). No further attempt is made to present it here since creep rates are dependent not only on stresses, but also on the environment. The environmental factors are temperature and type of fluid inside and outside the tube.

The author recommends rigid polyvinyl chloride as the best thermoplastic material for most applications in dry cooling towers. This does not mean, however, that the author believes thermoplastics to be the most desirable type of material. Further comparisons are made in Chapter VI.

D. Fillers for Polymers

Further complexity is introduced as soon as one adds fillers to the base resin to increase thermal conduc-

TABLE IV

PROPERTIES OF SELECTED THERMOPLASTICS (8, 15, 17)

| | Polyvinyl Chloride (rigid) | Polycarbonate | Polyethelene (high density) | Polypropylene |
|--|-------------------------------|-------------------------|--------------------------------|---------------------------|
| Cost (\$/16.)* | 0.16 | 1.175 | 0.265 | 0.30 |
| Cost (\$/Ft. ²)* | 0.10 | 0.72 | 0.17 | 0.19 |
| Tensile Strength (psi) | 5.5-9 x 10 ³ | 8-9.5 x 10 ³ | 3.1-5.5 x 10 ³ | 4.3-5.5 x 10 ³ |
| Compressive Strength (psi) | 10-11 x 10 ³ | 12.5 x 10 ³ | 2.7-3.6 x 10 ³ | 5.5-8 x 10 ³ |
| Flexural Yield Strength (psi) | 8-15 x 10 ³ | 13.5 x 10 ³ | 2-3 x 10 ³ | 6-8 x 10 ³ |
| Flexural Modulus (psi x 10 ⁵) | 2-6 | 3.4 | 1.0-2.6 | 2.0-2.4 |
| Elongation to Failure | 200-450% | 100-130% | 50-600% | 10-700% |

* See Table II.

TABLE IV. (cont.)

PROPERTIES OF SELECTED THERMOPLASTICS

| | Polyvinyl Chloride (rigid) | Polycarbonate | Polyethelene (high density) | Polypropylene |
|---|-------------------------------|-------------------------|--------------------------------|--------------------------|
| Thermal Conductivity (BTU/HR-Ft-F) | 0.1-0.2 | .11 | .07 | .07 |
| Thermal Coefficient of Expansion in/in/oF x 10 ⁻⁶ | 28-55 | 39 | 61-72 | 55-111 |
| Burning Rate (in./min.) | Self Extinguishing | Self Extinguishing | Slow | Slow |
| Effect of Sunlight | Good Resistance | Slight Embrittlement | Crazes if unprotected | Crazes if unprotected |
| Effect of Weak Acids | Good Resistance | None | Very Resistant | None |

TABLE IV. (cont.)

PROPERTIES OF SELECTED THERMOPLASTICS

| | Polyvinyl Chloride (rigid) | Polycarbonate | Polyethelene (high density) | Polypropylene |
|-----------------------------------|-------------------------------|---|--------------------------------|---------------------------|
| Effect of Strong Acids | Good Resistance | Attacked Slowly | Attacked Slowly | Attacked Slowly |
| Effect of Weak Alkalies | Good Resistance | Limited Resis- tance | Very Resistant | None |
| Effect of Strong Alkalies | Good Resistance | Attacked | Very Resistant | Very Resistant |
| Effect of Organic Solvents | Good Resistance | Soluble in aromatic and chlorinated Hydrocarbons | Resistant (below 176F) | Resistant (below 176F) |
| Glass Transition Temperature** | 190F | 302F | -184F | 14F, -4F |

**See Table III.

tivity, flame resistance, or strength. For example, reference (11) reports that mixing 100 parts epoxy with 130 parts aluminum powder increases the thermal conductivity of the epoxy by a factor of four. Only 40 parts of aluminum powder are required to double the thermal conductivity, however.

Since the thermal conductivity of aluminum powder is approximately 600 times that of epoxy, the long-term effects of filling a plastic with a metal powder may also be quite dependent on such things as mesh size of the powder, particle shape, particle orientation, plastic-filler interface contact and differences in coefficients of thermal expansion.

Again, one can conclude that the accurate appraisal of the physical properties of the end product will depend on the capability of reproducing the samples tested on the production line. The most reliable way to accomplish this is to make the samples on a normal production line, using different base resins with the same percentages of desired fillers. This approach may be impractical and very expensive.

Other characteristics such as internal stresses due to fabrication, fatigue properties, inelastic strain (plastic flow), impact strength, and hardness are measured using methods similar to those used for metals. Such characteristics are also significantly affected by the fillers and fabrication methods used, however. (See references 10, 12 and 13).

Thermoplastic materials are extrudable and may be filled with various percentages of a number of fillers. These fillers will, of course, affect the overall properties as well as the cost. Since the thermal conductivity of most thermoplastic materials is less than that required for an effective heat transfer medium, it is anticipated that fillers must be added which will enhance this property.

Reference (15) lists the various fillers which are suitable for this application. Table V shows that there are two types of fillers recommended for this purpose: metal oxides and metal powders.

It should be pointed out, however, that these are merely the fillers which are recommended. It is possible that other fillers, such as silica, may also be suitable as a result of their extremely low cost. For instance, aluminum oxide costs about 15¢ per pound (by the carload) and silica is only 1.5¢ per pound (by the carload), ⁽⁹⁾ a factor of ten difference. Thus, it is obvious that, on the basis of the low cost criterion, one must develop some measure of merit for these various fillers that compares thermal conductivity and cost on a "ball-park" scale and then include additional engineering factors to select the most promising candidates.

The obvious difficulty here is that the thermal conductivity of the filled plastic may be a strong function of the mesh size of the powders added. Also, the data available concerning the thermal conductivity of substances

TABLE V

FILLERS RECOMMENDED FOR INCREASING THE
THERMAL CONDUCTIVITY OF PLASTICS

METALLIC POWDERS (15)

ALUMINUM
BRONZE
LEAD
STAINLESS STEEL
ZINC

METALLIC OXIDES (15)

ALUMINUM OXIDE
BERYLLIUM OXIDE
MAGNESIA
TITANIA
ZINC OXIDE

OTHERS

GRAPHITE
SILICA
GLASS POWDER

in the powdered form can only be approximate, due also to the large variation in particle sizes and degree of "tamping". In addition, it may be argued that the thermal conductivity and density of the "fused" material are more appropriate in establishing a frame of reference. Using data available in the literature,^(9, 10) and keeping these points in mind, an overall comparison such as that in Table VI may be developed. This representation only provides an order-of-magnitude comparison of the various fillers, but it does give a basis for preliminary selection.

Table VI shows that graphite and glass powder are probably the most economic fillers which would increase the thermal conductivity of polymers.

In Chapter VII is presented the results of computer analysis of the effects of various composite materials on the economics of dry cooling towers.

TABLE VI

SELECTION OF POSSIBLE FILLERS FOR INCREASING THE THERMAL
CONDUCTIVITY OF POLYMERS

Design Criteria: Maximize $(K/\$xD)$

| FILLER | K(BTU/HR-FT-F) | \$(\$/lb) | D(lb/ft ³) | (K/\$xD) |
|-----------------------------|----------------|-----------|------------------------|----------|
| GRAPHITE | 87 | 0.06 | 135 | 10.74 |
| GLASS POWDER | 0.5 | 0.0018 | 162 | 1.71 |
| SILICA POWDER, AMORPHOUS | 0.8 | 0.015 | 145 | 0.368 |
| ALUMINUM POWDER | 119 | 3.30 | 165 | 0.219 |
| IRON POWDER | 39 | 1.58 | 450 | 0.0549 |
| BERYLLIUM OXIDE | 129 | 49.28 | 189.2 | 0.0138 |
| ALUMINUM OXIDE | 17.5 | 0.15 | 247.5 | 0.00471 |

E. Weatherability of Polymers

Another important topic of concern in any discussion of materials is that of weatherability. Reference (14) details many of the aspects of polymer degradation due to exposure to the weather and atmospheric pollutants. The most relevant of these are presented here.

Polymer degradation may result from exposure to sunlight, oxygen, ozone, NO_2 or SO_2 . Sunlight's frequency band is near the frequency at which the carbonyl groups in polymer chain absorb energy, introducing sufficient energy to break the carbon-carbon bond. Thus, the constant exposure of a plastic to sunlight can have significant effects, and such exposure should be avoided.

Oxygen causes plastics to deteriorate by diffusing into the plastic and interacting with the polymeric chain chemically. The presence of ultraviolet light accelerates the reaction by providing energy and the end result (after several intermediate chemical reactions) is cross-linking of the polymeric chains and consequent embrittlement of the plastic.

Ozone, in even very small concentration, attacks polymers which are under a certain minimum load. Cracks are first formed near the surface of the plastic, the load causes additional polymer chains to be exposed to the ozone and the cracks propagate through the material, eventually causing failure. In the absence of a stress, a protective layer forms and prevents further deterioration due to ozone.

Atmospheric pollutants degrade polymers in a similar fashion and, thus, deposits of particulate pollutants and film from droplet dispersions should be avoided or washed off plastic surfaces.

Various artificial light sources have been used to approximate the frequencies and intensities of sunlight: carbon arcs, fluorescent lamps, mercury arcs, and xenon arcs. Of these, the xenon arc comes closest to representing the spectral energy distribution of sunlight.

Accelerating the effects of sunlight using these artificial sources, however, frequently produces results which do not correlate accurately with natural sunlight. This is due not only to the different spectral distributions, but also to the time dependent nature of the chemical reactions involved and the action of secondary reactions promoted by temperature, moisture and oxygen.

Some researchers have used mirrors to intensify the sunlight on test samples, thus maintaining the relative spectral distribution. Although special mirrors and cooling units are required, this may be the best manner in which to obtain data on the relative merits of plastics that have similar secondary reactions. Again, even this approach is only an approximation due to the relationships between chemical bond strength and radiant energy levels. Stronger bonds may not be affected at all by normal exposure, but fail rapidly at concentrated levels of sunlight.

IV. Glasses and Ceramics

Early in the search for an inexpensive material with adequate thermal conductivity for dry cooling towers, it was noticed that glass materials have, in general, thermal conductivities well above those of most plastics. In fact, it would be tempting to place primary emphasis in this paper on glass materials instead of plastics. The various engineering problems associated with glasses, however, make them somewhat undesirable for long-term service.

The principal problem, of course, is their brittleness and sensitivity to stress raisers. This sensitivity causes the breaking stresses to be random and difficult to predict. As a matter of fact, reference (16) recommends using a statistical approach to determine strength. If this characteristic is coupled with the fatigue properties of glasses, a large assemblage of thin-walled glass pipes could require almost continuous replacement in inaccessible locations.

These fatigue properties are such that the breaking stress of glass decreases with increased duration of load. This decrease can be as much as 40%, and is not dependent on cyclic stresses. That is, static loads cause fatigue in glasses similar to the cyclic loading of metals.

Another observation which may be made is that the failure of a single glass tube in a large assembly may lead to a chain reaction in which some (or all) of the tubes below it would fail.

Failure of brittle materials is usually sudden and total. Ductile materials such as plastics fail after considerable elongation and, thus, may be used in a cooling tower without fear of a total plant shut down due to sonic booms or mild earthquakes.

Of course, thicker sections of glass may prevent such failure, but at the expense of reduced overall thermal conductivity and increased susceptibility to thermal shock. Also, since stress concentrations occur at mounting points, a margin of safety of 100% is generally recommended,⁽¹⁶⁾ and resilient gaskets must be used to separate glass from glass, glass from ceramics, or glass from metals. Stresses due to differences in coefficients of thermal expansion change extremely fast if glass is in direct contact with another rigid material.

Ceramics differ from glasses in that glasses have a random atomic structure (similar to a liquid state) and ceramics have a discrete crystal structure. Although ceramics are not as sensitive to surface conditions (cracks) as glass, they are generally much more expensive and difficult to fabricate.

There is some speculation that glass piping covered with a protective coating of a plastic material might prove advantageous. It can be readily shown that only a soft, thin material could be used and that in a cooling tower such a material on the inside of the tubes would be eroded by the flow of hot water. This leaves the outside of tubes

protected, however, and as long as the material is weather-resistant and can tolerate the elevated temperature for a long period of time, it might prove useful.

A solid coating, however, would be required to protect the glass and this would inhibit heat transfer. Also, the unavoidable differences in coefficient of thermal expansion may deteriorate the thermal conductivity at the interface over a period of time.

As stated in the chapter on polymers, the glass-transition temperature separates plastics and rubber and plasticizers can be used to lower this temperature. Thus, a soft (rubbery) coating would probably contain some plasticizing material. Such additives cause the material properties to be sensitive to temperature changes due to varying solubilities with temperature and the consequent migration or loss of plasticizer. This loss also may occur due to sublimation over a period of time. Consequently, one might expect the coating to gradually lose flexibility and cause failure of the glass which it is "protecting" or (alternatively) crack and flake off like paint.

It is possible that a very thin coat of a plastic material could be applied to the outside of glass pipe during manufacture such that the glass is placed in compression. During subsequent thermal transients the effects of the differences in thermal expansion would be minimized. It is expected, however, that such an arrangement would degrade relatively rapidly due to the viscoelastic nature of the plastic which would soon relieve these "residual" stresses.

Also, there is a glass-to-plastic interface degradation phenomenon which occurs in the presence of water or high humidity.

A recently developed process which is somewhat similar to the above is one where the glass surfaces may be placed in compression by means of a chemical reaction. Sodium atoms are replaced by potassium atoms during immersion of the glass in a chemical bath. Since the potassium atoms are larger than the sodium atoms, compressive forces are introduced. The resultant product is extremely strong and the chemical process is not expensive. Further data on this process needs to be accumulated.

Of the presently available glass piping systems, the borosilicates (i.e., PYREX[®], KIMAX[®], and DURAN 50[®]) are the most popular due to their strength, temperature resistance, and moderate cost. These piping systems are used frequently in the chemical industry since they also are resistant to chemical attack.

Glass heat exchangers are also available in various forms ranging from small laboratory condensers, to large tube and shell varieties, and to even larger module forms similar to that needed for cooling tower applications. For example, Corning Glass Works (Corning, New York) markets a PYREX[®] heat exchanger module that is normally used in cascade applications. That is, the cooling fluid is allowed to "waterfall" over the outside of the tubes.

These particular heat exchanger tubes are reinforced near the ends of the tubes by increasing the wall thickness and tempering. Thus, the required strength is ensured without affecting the heat transfer characteristics significantly.

These special fabrication requirements increase the cost of such heat exchangers to the point where they are no longer competitive with finned tube counterparts. Ideally, the inexpensive material cost of glass must be matched with an inexpensive, simple cooling tower design.

V. Glass Fiber Reinforced Plastics

One characteristic of glass that has not yet been discussed is that thin glass fibers are much stronger than relatively thick sections. When these fibers are combined with a plastic material, a very strong composite is formed. The material can be stronger than steel and lighter than aluminum, making fiberglass reinforced plastics (FRP) desirable in many engineering applications.

It is tempting to include this discussion under the heading of Fillers for Polymers; however, there is a sufficient body of separate information applicable to FRP's that a separate chapter is warranted.

For instance, unlike most other fillers, glass fibers are supplied as continuous strands, fabrics, mats, and chopped strands. These filler forms may be used with thermoplastics or thermosets and approximately 90% of all plastic reinforcement is by use of glass fibers.

A. Types of FRP's

Of the various types of glass fiber fabrication, filament winding is the most expensive, but produces much higher tensile and bending strengths. Thus, for "equal performance", it can be shown⁽⁶⁾ that filament wound-epoxy is less expensive than any other material in applications which require strength in certain directions.

Also, unlike other fillers, the more glass that is added, the stronger the composite material, and the relationship is almost linear. Strength also depends on

the orientation of the glass fibers. The strongest materials have continuous strand, unidirectional glass fibers. The next strongest classification is the bidirectional (fabric) filler. The least strong is "chopped strand" since here the fibers are randomly oriented. Depending on the application, however, strength may be required in more than one or two directions, so it may not be possible to utilize the "strongest" material in any particular design.

The most commonly used resins in the FRP industry are polyesters since they are more economical. Several other thermoset resins are used (epoxies, phenolics, silicones, melamines, acrylics) and some thermoplastic resins have also been reinforced with glass (polystyrene, nylon, polycarbonates, acetals).

If filament winding is to be used, thermoset resins are desirable, but if extrusion is desired, a thermoplastic is necessary. It should be understood that thermosets, in general, are more chemical and temperature resistant than thermoplastics. Their major drawback is manufacturing time since a curing time is involved.

B. FRP Degradation

Based on the foregoing, it would appear that FRP's are far superior to other materials and that our problems are over. Nevertheless, there is a basic long-term degradation phenomenon associated with FRP's that makes their use questionable, especially in the presence of hot water.

Reference (18) goes into detailed descriptions concerning the micromechanics and the fiber-matrix interface problems associated with these materials. Significantly, one paper (McGarry) describes the crack propagation resistance of the base resin, which in turn is related to the fatigue strength of the composite material. For example, reduction in strength to the point of "gross cohesive failure" may occur in less than 100 fatigue cycles at stresses of 50 to 70% of the ultimate tensile strength. Resistance to water and chemical attack also diminish with cyclic stress.

More importantly, cracking may start even as a result of a single fatigue cycle below 20% of the ultimate tensile strength. The first cycle of stress accounts for a larger amount of damage than any subsequent cycle. The cracks usually start at voids or at points where the glass fibers are close or touch, and the cracks are usually caused by components of tensile stress perpendicular to fiber bundles.

Thus, although FRP's increase in strength with increased glass fiber loading, their resistance to fatigue damage decreases. It becomes necessary to optimize the fiber spacing and to use a resin which is resistant to crack growth.

McGarry also reports that the resin matrix may be toughened by additions of elastomeric (rubbery) materials to the resin, thus inhibiting crack propagation. Specifically

identified as successful materials are butadiene-acrylonitrile additions. Samples of composites containing such additives did not crack even in the presence of severe fatigue loading, according to McGarry.

Besides such cracking problems, the matrix-glass fiber interface bond deteriorates in the presence of boiling water. Specifically the water attacks and removes the coupling agent used to obtain a good bond between the matrix and glass fibers. In some composite materials 90% removal occurs after exposure to boiling water for only two hours according to the paper by Johansson (et al.) in reference (18).

Other papers in the same book describe various coupling agents (especially silane coupling agents) and their relative effectiveness in creating a matrix-glass fiber bond in the fabrication of materials which must be able to withstand boiling water. Most important among the points made are that water must not be present during the fabrication process if maximum bond strength is to be realized and that, in general, coupling is more effective when thermosets are used than when thermoplastics are used. Sterman and Marrden point out that some thermoplastics are more reactive (bondable) than others, but that a great deal of work needs to be done since the bonds are extremely sensitive to the time-temperature relations and to the types and amounts of additives used.

For the purposes of this paper, however, no encouraging data is available on the effects of hot water over long-

term exposure of FRP's. Much empirical data has been presented in the literature concerning the water degradation of FRP's, but no significant progress has been made in solving the problem itself.

VI. Material Selection

Having considered the various properties of polymers, fiberglass reinforced plastics and glass materials, the time comes when a rational selection process must be developed. Such selection may not produce the optimal recommendation for all of the possible dry cooling tower designs, but some relative ordering can be established to assist in the design analysis.

A. Summary of Basic Properties

Figure VII is a summary of the basic characteristics, pro and con, of thermoplastics, thermosets, fiberglass reinforced plastics, and glass. These are highly generalized qualities and not necessarily applicable to any specific material. Likewise, the generalized data in Table VIII are only for gross comparisons of the material properties. Aluminum is included in Table VIII for comparison purposes.

Due to the problem of creep in thermoplastics, cyclic stress degradation of fiberglass reinforced plastics, and the non-cyclic fatigue degradation of glass, it is necessary to compare these materials in two different design cases. First, they must be compared in terms of horizontal tube design and, secondly, in terms of vertical tube design.

B. Horizontal vs. Vertical Tubes

Horizontal, thin walled tubing (.060 inch) will deflect significantly over the unsupported distances normally expected in cooling tower heat exchangers (10 to 20 feet),

TABLE VII

QUALITATIVE SUMMARY OF MATERIALS

| THERMOPLASTICS (Polycarbonate, PVC, Polyethy- lene) | THERMOSETS (Epoxy, Polyester) | FIBERGLASS REINFORCED PLASTICS | GLASS |
|--|-------------------------------------|--|--|
| <u>ADVANTAGES</u> | | | |
| Extrudable | Low Creep Rates | Very Low Creep Rates | Base Material Very Inexpensive |
| Inexpensive Fabrication | High Temp. Resistance | High Temp. Resistance | Extrusion Very Inexpensive |
| | High Chemical Resistance | High Chemical Resistance | High Temp. Resistance |
| | | High Strength | High Chemical Resistance |
| | | Low Coefficients of Thermal Expansion | High Thermal Conductivity |
| | | | Low Coefficients of Thermal Expansion |
| <u>DISADVANTAGES</u> | | | |
| High Creep Rates | Generally Not Extrudable | Long Term Degradation by Water | Brittle |
| Generally Low Chemical Resistance | Curing Time Required | Strength Degradation Due to Cyclic Stresses | Sensitive to Stress Raisers |
| Generally Low Strength at Moderate Temp. | Low Impact Strength | Higher Cost | Non-Cyclic Fatigue Degradation |

TABLE VII (Cont.)

Low Thermal
Conductivity

Low Thermal
Conductivity

High
Coefficients
of Thermal
Expansion

Moderate
Coefficients
of Thermal
Expansion

TABLE VIII

SIMPLIFIED COMPARISON OF MATERIAL PROPERTIES

| | K (BTU/HR-FT-°F) | DENSITY (lb./in ³) | TENSILE STRENGTH (psi 10 ³) | THERMAL EXPANSION in./in./°F x 10 ⁻⁶ | FLEXURAL MODULUS psi x 10 ⁶ |
|---|---------------------|-----------------------------------|--|--|--|
| THERMOPLASTICS (Polycarbonate, PVC, Nylon, Polypropylene) | 0.1 | 0.03-0.05 | 4-10 | 30-110 | 0.1-0.5 |
| THERMOSETS (Epoxy, Polyester Phenolic) | 0.1 | 0.05-0.08 | 3-10 | 10-40 | 1-3 |
| FIBERGLASS REINFORCED PLASTICS | 0.2 | 0.05-0.08 | * | 2-20 | 1-7 |
| GLASS | 0.4-0.6 | 0.08-0.09 | 10 | 2-5 | 10 |
| ALUMINUM | 113-130 | 0.09-0.10 | 6-27 | 12-13 | 10 |

* Filament Wound Epoxy 80-250
 Fiberglass Fabric-Epoxy 50-70
 Fiberglass Premix-Polyester 5-10

especially at small tube diameters. For example, a simply supported 1.0 inch ID, 0.060 inch wall, 20 foot length of water filled tube with a 2 inch mid-point deflection limitation would have to have a flexural modulus of almost 100×10^6 psi. This is well above the capability of common materials. Fixed end supports would lower this required flexural modulus by only a factor of 5. Some metals would then be able to meet this flexural modulus, but not polymers or fiberglass and not even aluminum.

However, the deflection varies as the ratio of the fourth power of length so that 10 foot tubes would need a flexural modulus of only 6×10^6 psi to keep mid-point deflection below 2 inches. No thermoplastics or thermosets and few FRP's can meet this (arbitrary) standard. Glass and aluminum could meet such a standard for 10 foot lengths.

Thus, although horizontal heat exchangers are made of relatively thick walled aluminum tubes in such lengths as ten to twenty feet, thin walled plastic designs would have to be supported (baffled) every few feet to avoid excessive fatigue cycles and contact between tubes caused by the weight and flow fluctuation of the water on the inside of the tubes.

The maximum local stress levels associated with the above examples (neglecting deflection criteria) range from about 100 psi for the 10 foot rigidly supported case to almost 600 psi for the 20 foot simply supported case.

These are relatively modest stresses except at higher temperatures. They also do not include thermal and dynamic stresses and fatigue effects.

These static stresses, however, are adequate to cause long-term problems with creep in thermoplastics. Adequate support must be provided.

Glass heat exchangers, on the market already, have .060 inch walls and ten foot lengths, but are made in 2 inch diameters (Corning Glass Works, Corning, New York). The small diameters required to get adequate heat transfer surfaces in a dry cooling tower make glass inappropriate for use in horizontal heat exchangers.

Having outlined the probable inadequacy of most materials in thin walled, horizontal tube designs, it would appear that vertical configurations are quite attractive. Here the tube material is subjected to far less stress and requires less support.

To understand some of the additional details associated with vertical designs, it is convenient to again refer to the Rugeley plant in England. Reference (19) provides additional data on their natural draft towers. Without getting into excessive details about the plant, a few points may be made. Most important is the effect of wind on the cooling tower. Cylindrical forms in a fluid field have a circumferential pressure distribution which produces low pressure areas at points 90 degrees from the direction of the fluid stream velocity vector. This may reduce or re-

verse the flow in a natural draft tower. To take care of this problem (more severe in vertical tube designs due to physical layout requirements) the Rugeley engineers designed the plant to operate on the segments of the cooling tower facing the wind and away from the wind during high wind conditions. The net result was that only a 0.4 inch Hg change in vacuum occurred with winds up to 30 miles per hour. This is, of course, only a minor effect and indicates that properly designed systems can compensate for wind problems by using segmented towers.

Rugeley also operates with a slight positive pressure (a couple of psi) at the highest water level in the tower in order to be able to keep air out of the system. Thus, the pressure at the bottom of the heat exchanger elements (48 feet) will be about 25 psi. This will result in a tensile (hoop) stress at the bottom of the tube of 283 psi for a 1 inch ID, 0.060 inch wall. The axial stresses depend upon where the tube receives its principal vertical support, but will be far less than the above stress in most cases. Only when thermal expansion of the tubes is constrained will excessive stresses be present.

C. Recommendations and Alternatives

Based on the assumption that non-metallic materials are at least strong enough to tolerate the stresses associated with the vertical tube design, and that wind problems have been minimized so that vertical heat exchangers are acceptable, some comparison of the basic materials considered in this report is in order.

A typical figure of merit analysis is presented in Table IX. Here the numbers are based on the presumption that a heat exchanger of vertical design with approximate stresses as outlined above is being built. Variations in design requirements could lead to totally different results.

Such comparisons as that in Table IX are of marginal value, but indicate that all of the categories of materials are approximately the same, except FRP's. If the heat exchanger surface were to be horizontal, however, FRP would probably be the best selection due to the higher strength requirements. Baffling support members, nevertheless, should not be ruled out (unless it becomes a matter of excessive cost) for any of the materials selected, either horizontal or vertical design.

TABLE IX

FIGURE OF MERIT MATERIAL SELECTION

| ITEM | MAX. | THERMOPLASTICS | THERMOSETS | FRP'S | GLASS |
|-----------------------|------|----------------|------------|-----------|-----------|
| MATERIAL COST | 10 | Average 5 | Average 5 | Higher 3 | Lower 9 |
| SERVICE LIFE | 10 | Lower 3 | Average 5 | Average 5 | Average 5 |
| FABRICATION COST | 10 | Lower 7 | Average 5 | Higher 3 | Lower 8 |
| ASSEMBLY COST | 10 | Average 5 | Average 5 | Average 5 | Higher 3 |
| DESIGN UNCERTAINTY | 10 | Average 5 | Average 5 | More 3 | More 3 |
| MAINTENANCE COSTS | 10 | More 4 | Average 5 | Average 5 | More 4 |
| TOTALS | 60 | 29 | 30 | 24 | 32 |

VII. Computer Analysis

An apparatus which has been used to determine the thermal conductivity of composite materials is the "colora thermoconductometer" described in reference (20). This device requires only a very small sample and utilizes various different liquids to establish temperatures on each side of the samples. The liquids have different boiling points and the one with the lower boiling point is recondensed, collected, and measured to determine the thermal conductivity of the sample.

There are a couple of drawbacks to this procedure. First, "calibrated" samples are required near the range of thermal conductivity to be tested. Second, different chemicals must be used for each test point and the chemicals themselves are usually flammable and toxic. The accuracy of the instrument is given as 3% compared to the calibrated samples. The device is also somewhat expensive and is sold by the Dynatech Corporation for \$3,495 (f.o.b., Cambridge, Massachusetts; vacuum pump and fluids not included).

This apparatus has been used by Sundstrom and Chen (21) to determine the thermal conductivity of glass-sphere reinforced plastics.

Their research was significant in that it verified the relation for the thermal conductivity of composite materials given in reference (22). An equation is provided which correlated well with low thermal conductivity composites as investigated by Sundstrom and Chen.

In addition, since varying the size of glass spheres used as fillers did not change the thermal conductivity of the composite significantly, they concluded that the thermal conductivity was a function of relative volumes and relative conductivities of the constituents and that the overall thermal conductivity is predictable by the Cheng-Vachon⁽²²⁾ equation as long as the ratio of the thermal conductivities of the filler and matrix materials is less than 100.

The Cheng-Vachon relation is:

$$\frac{1}{K_e} = \frac{1-B}{K_c} + \left(\frac{1}{\{C(K_d - K_c)(K_c + B(K_d - K_c))\}^{1/2}} \right) \times \left(\ln \left[\frac{(K_c + B(K_d - K_c))^{1/2} + \frac{B}{2}(C(K_d - K_c))^{1/2}}{(K_c + B(K_d - K_c))^{1/2} - \frac{B}{2}(C(K_d - K_c))^{1/2}} \right] \right)$$

where K_e = equivalent thermal conductivity of the composite

K_d = thermal conductivity of the discrete phase.

K_c = thermal conductivity of the continuous phase.

Φ = volume fraction of the discrete phase.

$$B = \left(\frac{3\Phi}{2} \right)^{1/2}$$

$$C = \left(\frac{2}{3\Phi} \right)^{1/2}$$

The availability of such an equation makes it possible to reduce to some degree the number of samples of composite materials required and may eliminate the need of investigating some combinations of materials entirely. For example, since the thermal conductivity of glass is only slightly higher than of thermoset materials, many fiberglass

reinforced plastics may be analyzed by the computer program by only knowing the ratios of the materials and their thermal conductivities (in the uncombined state).

A. Description of the Original Program

The complexity of the original computer program precludes attempting to describe it in detail here. Reference (2) is a necessary complement to this work if it is desired to reproduce the analysis and appreciate the computer program's design optimization process.

The principal difference between this program and previous programs dealing with the same subject of optimizing cooling tower designs is that in the past the analysis has been based on pre-designed heat transfer modules. The program described in reference (2), however, designs the heat exchanger module and integrates it with the total power plant design. It then calculates the capital costs and annual costs of the cooling tower, including the effects of lost efficiency. Using a search technique that varies the design slightly, continues to recalculate until the minimum cost is found.

The input data consists of such information as fan blade costs, boiler costs, fuel costs, replacement power costs, interest rates, heat exchanger surface performance, and base thermal efficiency.

Output from the program consists of the net cost of operation, the design configuration of the heat exchanger surface, and required flow rates of water and air. Calculations are repeated for various design ambient air temperatures

(60F to 100F) and the results may be compared to obtain the optimal. The design ambient air temperature (TD) is defined as the maximum ambient air temperature at which the power plant can generate 100% of its rated capacity.

The heat exchanger surfaces for which the program was used in the past have been finned tubes or packed beds. The present work makes the program more flexible by allowing calculations for bare-tubed designs and low thermal conductivity materials such as glass, plastics, and composite materials. This is accomplished without affecting the program's previous capabilities.

B. Modifications to the Existing Computer Program

The economic analysis of the various heat exchanger surfaces described in reference (2) were based on cost data taken from reference (23). There the data is presented in graphical form. The computer program utilizes this information by a polynomial curve fit so that a series of constants is required as input data. Expected savings may be reflected in capital costs by multiplying these constant values by the appropriate factor.

Selection of the proper cost factor is not a simple matter, however, since the actual costs involved with building a cooling tower include not only materials, but also labor and overhead. Since cooling towers have not been made from polymer or glass materials in the past, the cost factor assumed will be a necessary component of the computer "results". Otherwise the data presented would be misleading and irresponsible.

One of the major savings associated with lightweight materials is, of course, the reduced handling costs. Simplified joining methods are also involved when non-metals are used, especially if quality control requirements are not too restrictive. In addition, larger prefabricated units may be produced at the factory and shipped at less expense than units made from relatively heavy finned tubes.

Professor Frederick J. McGarry at MIT suggested that structures such as cooling towers could be built from fiberglass reinforced plastics at about one-fifth the cost of metallic units. Such optimistic appraisals are encouraging; however, no realistic data is available to support such estimates.

In this context then, the most profitable and legitimate approach to the cost problem is to perform computer runs for a different cost factor and present the results for the reader's guidance.

The most complicated change to the computer program is the introduction of a new subroutine (TCL0W) which takes into account the low thermal conductivity of the tube wall. Previous to this analysis, the heat transfer medium (aluminum, for example) has not affected the overall coefficient of thermal conductivity (U) significantly since the major resistance to heat flow has been the air side surface coefficient.

Subroutine TCL0W was written such that the Cheng-Vachon equation would be used if appropriate composite

material data is inserted. Thus, if the thermal conductivity of the continuous (matrix) material (TCCON), the thermal conductivity of the discrete phase (TCDIS) and the volume fraction of the discrete phase (VOLDIS) are included with the wall thickness (WALL) as input data, the equivalent thermal conductivity (TCEQ) is calculated for the composite material and used in the standard equation for U.

If the heat exchanger surface is not a composite material, TCEQ may be inserted as input data in lieu of TCCON, TCDIS and VOLDIS. If the input data card reserved for TCLOW is blank, the entire main program reverts to finned tube and packed bed calculations automatically and the related data cards must include data for one of these other types of heat exchanger surface.

The only other complexity involved in setting the program up to analyze bare-tubed vice finned-tube heat exchangers is selecting appropriate bare-tube arrangements and dimensions from reference (24), London and Kays, as was done for finned tubes in previous work. This allows one to obtain valid (empirical) heat exchanger data (surface coefficient and frictional losses), but constrains the analysis to the few types of bare-tubed surfaces for which the required data is available. (The input data affected are FAC, FAS, SAC, and SAS.)

Less complex is the alteration of the original data set and main program to coordinate the automatic identification of the type of heat exchange surface being

analyzed. The input data for the fin diameter (DFIN) is set equal to the outside diameter (OD) and the fin thickness (THFIN) is set equal to zero. The packed bed ball diameter (BEDIA) is also set equal to zero.

The program logic will then look for the bare-tube data described above, calculate and print the equivalent thermal conductivity of the wall and also store it as TCEQ. This calculation is made only once since the computation is by-passed whenever TCEQ is non-zero.

C. Comparison of Results With Previous Data

Data for cost factors of 1.0, 0.5, and 0.2 applied to a specific bare tube design are given in table X. Since glass represents the best expected thermal conductivity among the materials discussed in this paper, data for a representative glass heat exchanger was used in the computer program. Some data from reference (24) is included in figure 1.

Reference (2) provides data for packed bed, finned tube, and plate finned heat exchanger surfaces. Various geometries of each type are compared. While it may be relatively accurate to compare the different geometries within each of these three types, it is of questionable validity to compare the types with each other. The principle variable which causes this problem is the cost input data.

This same problem arises in attempting to compare these heat exchanger surfaces with bare tubes. The approach taken here is to provide the reader with a range of data in order to fully embrace

the range of possibility. This will indicate the approximate cost factor required to make the non-metallic surfaces competitive.

Figure 1 gives capital cost vs. design ambient temperature results of computer runs with cost factors of 1.0, 0.5, and 0.2. As in reference (2), the sum of the capital cost for tower construction (CCOS) and the cost of additional boiler capacity due to thermal inefficiencies (CBOIL) are added to obtain the true capital cost. In figure 2 the 0.5 and 0.2 curves from figure 1 are compared with the comparable curves from reference (2) for packed bed and finned tube heat exchangers.

As shown in figure 2, a cost factor of 0.5 (50% less expensive construction and material costs) would make bare tubed designs almost competitive in the capital cost area. A lower cost factor such as 0.2 (80% less expensive construction and material costs) would obviously make non-metallic surfaces look better, but in an approximate analysis such as this it is of marginal credibility and may be misleading since the actual cost factors can only be estimated.

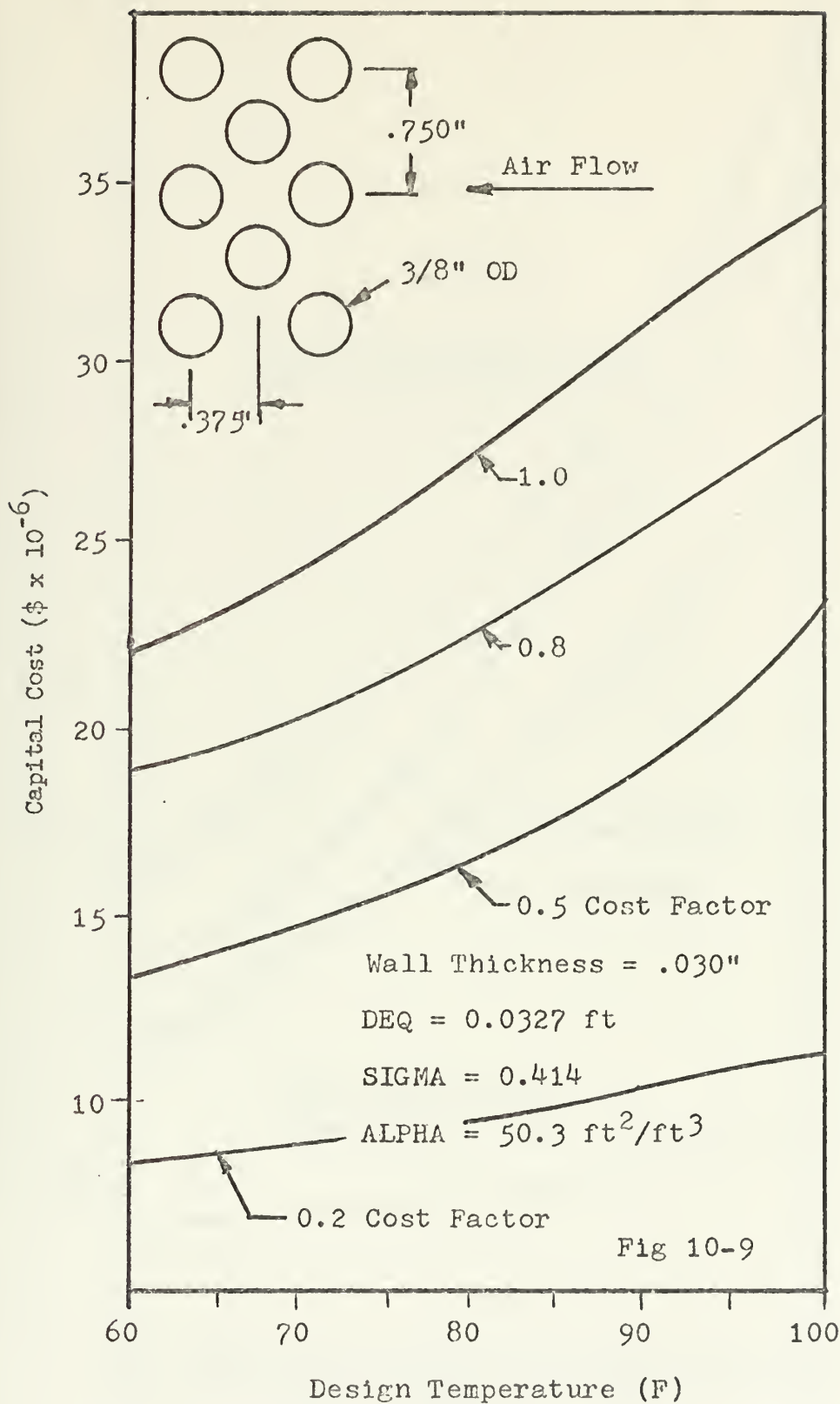
Figures 3 and 4 compare the total annual costs for these heat exchange surfaces based on the incremental ambient temperature distribution described in reference (2). The computer output term associated with this calculation is ACOS. These figures also show that the 0.2 cost factor curve compares well with the packed bed and finned tube curves.

At the point of minimum cost, each of these curves indicates that the optimal design temperature is in the vicinity of 75 F. Thus,

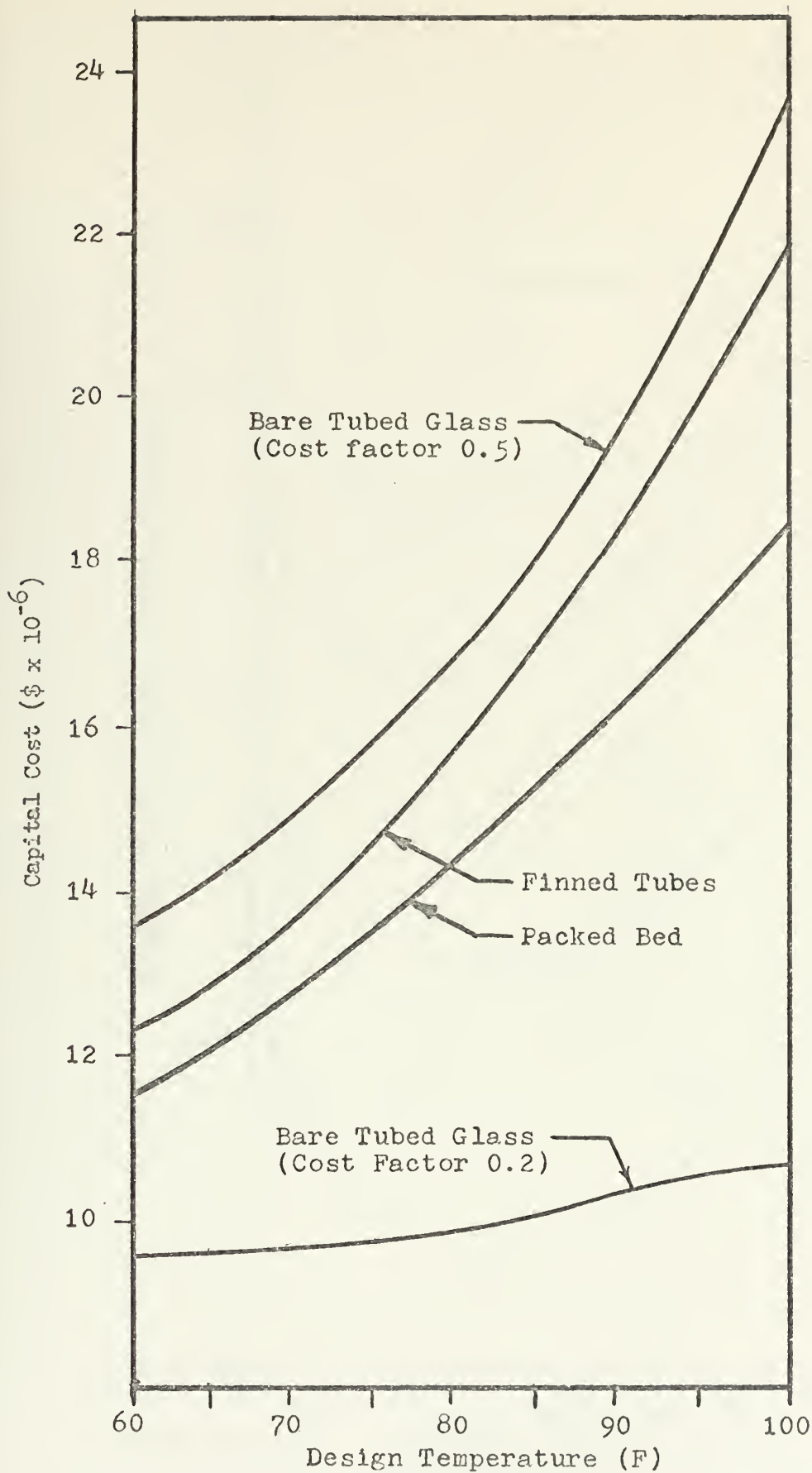
detailed computer output for the various surfaces is given in tables X and XI for the design temperature of 75 F.

The extra operating cost shown for non-metallic surfaces is due mostly to the need to provide additional fan power to obtain the minimum air side pressure drop invoked by the computer program. Even the 0.2 cost factor value is more than 26% above that for finned tubes. Also, the slightly higher turbine exhaust temperature (T1) leads to a decreased thermal efficiency for the power plant and, consequently, higher fuel costs.

A possible solution to this extra cost would be to use non-metallic heat exchanger surfaces in natural draft cooling towers. The net effect on interest charges on increased capital costs may easily overcome such savings in operating cost, however.

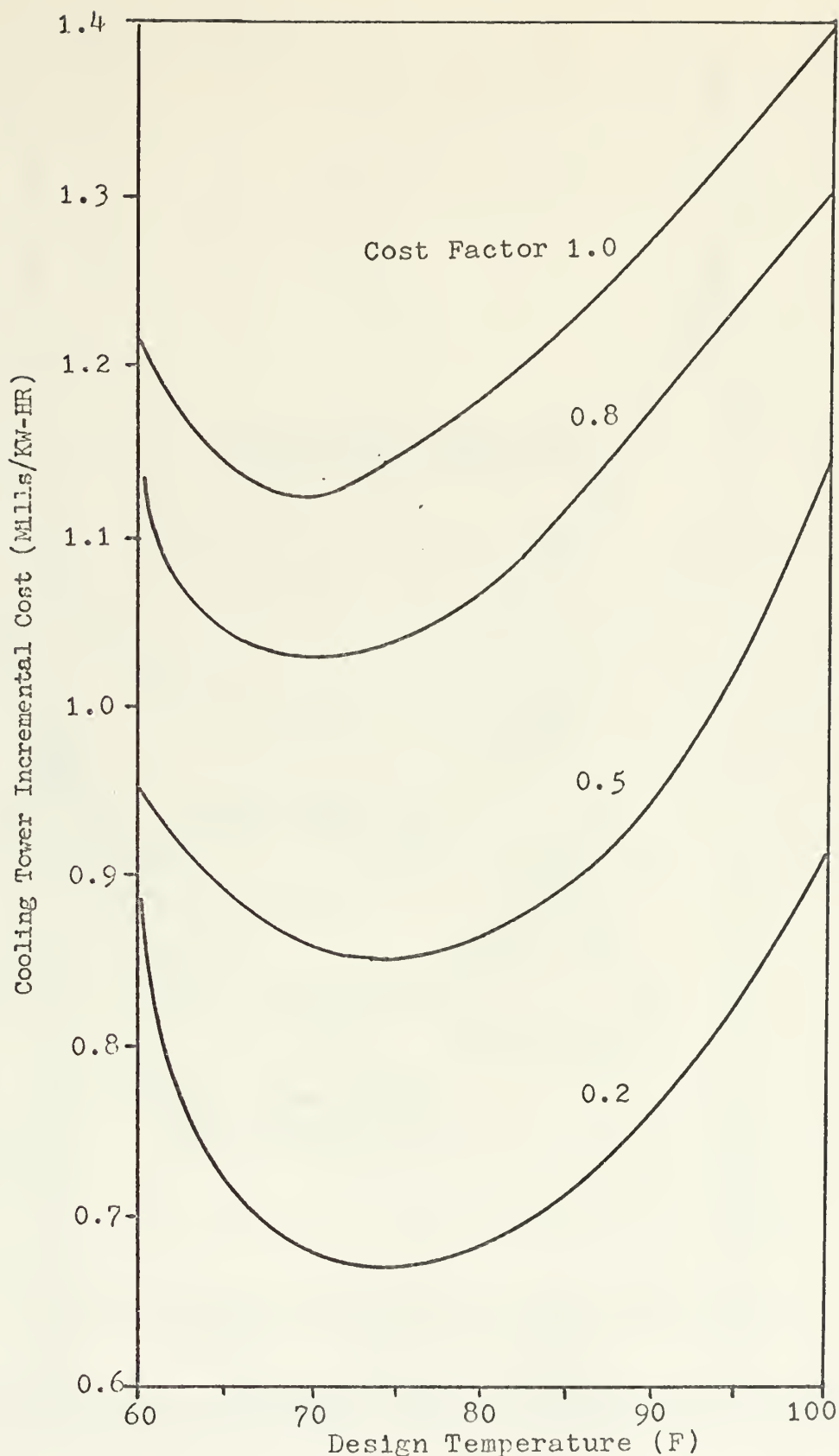


COOLING TOWER CAPITAL COST VS. DESIGN TEMPERATURE
For Dry Cooling Tower Using Bare Glass Tubes
Figure 1

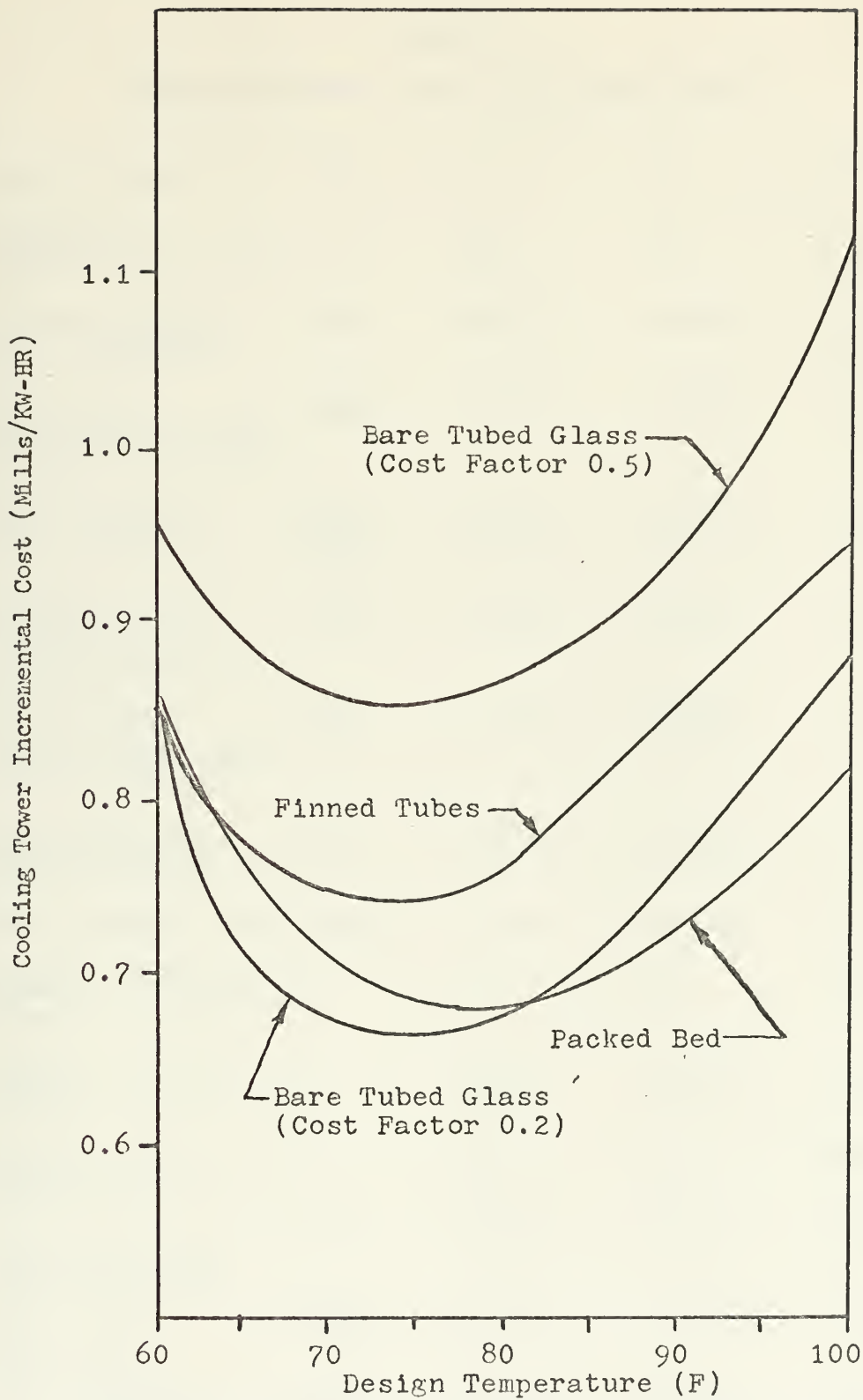


COOLING TOWER CAPITAL COST VS. DESIGN TEMPERATURE
For Various Types of Dry Cooling Towers

Figure 2



COOLING TOWER INCREMENTAL COST VS. DESIGN TEMPERATURE
For Dry Cooling Tower Using Bare Glass Tubes
Figure 3



COOLING TOWER INCREMENTAL COST VS. DESIGN TEMPERATURE
For Various Types of Dry Cooling Towers

Figure 4

TABLE X

COMPUTER RESULTS FOR BARE GLASS TUBES*

| Cost Factor | CRF | 1.0 | 0.5 | 0.2 |
|--|-------------|--------|--------|--------|
| Design | | | | |
| Temperature (F) | TD | 75 | 75 | 75 |
| Tower Capital Cost (\$x10 ⁻⁶) | CCOS | 23.701 | 13.888 | 7.147 |
| Cost of Increased Boiler Capacity (\$x10 ⁻⁶) | CBOIL | 1.742 | 1.838 | 1.855 |
| Net Capital Cost (\$x10 ⁻⁶) | CCOS+ CBOIL | 25.443 | 15.726 | 9.002 |
| Constant Temp. Total Cost (Mills/Kw-Hr) | TCOS | 1.1788 | .91011 | .71902 |
| Incremental Temp. Total Cost (Mills/Kw-Hr) | ACOS | 1.1362 | .86488 | .67331 |
| Operating Cost (Mills/Kw-Hr) | OCOS | .36234 | .33467 | .31482 |
| Tube Length (Ft) | LENGTH | 6.646 | 12.449 | 23.217 |
| Number of Tubes Deep | N | 11 | 12 | 13 |
| Number of Tubes Wide | NW | 549542 | 296595 | 157122 |
| Turbine Exhaust Temp. (F) | T1 | 139.2 | 140.2 | 140.3 |
| Heat Exchanger Effectiveness | EFF | .5102 | .5232 | .5498 |
| Water Temp. Drop (F) | RANGE | 2.509 | 6.798 | 8.974 |
| Air Velocity (Ft/Sec) | VAIR | 27.912 | 26.620 | 25.590 |

TABLE X (Cont.)

COMPUTER RESULTS FOR BARE GLASS TUBES

| | | | | |
|--|-------|----------|----------|---------|
| Water Velocity (Ft/Sec) | VWAT | 2.1 | 1.3 | 1.7 |
| Fan Power (KW) | FPOW | 23698 | 22170 | 20663 |
| Pump Power (KW) | PPOW | 457.0 | 140.8 | 323.8 |
| Air Side Frontal Area (Ft ²) | AFRON | 288270 | 203770 | 227990 |
| Width of Air Side (Ft) | WIDTH | 34346 | 18537 | 9820 |
| Width to Length Ratio | WLRAT | 5167.844 | 1489.048 | 442.974 |
| Ratio of Heat Capacity of Water to That of Air | CWARA | 13.0571 | 5.0146 | 4.0018 |

TABLE XI
COMPARISON OF VARIOUS HEAT EXCHANGERS

| Surface | <u>Packed Bed</u> | <u>Finned Tube</u> | <u>Bare Glass Tubes</u> | |
|---|-------------------|--------------------|-------------------------|--------|
| Cost Factor | 1.0 | 1.0 | 0.2 | 0.5 |
| Power Generated (MW) 1000 | | 1000 | 1000 | 1000 |
| Design Ambient Temperature (F) 75 | | 75 | 75 | 75 |
| Incremental Total Cost (Mills/Kw-Hr) | .68391 | .72960 | .67331 | .86488 |
| Operating Cost (Mills/Kw-Hr) | | .25306 | .31482 | .33467 |
| Constant Temp. Total Cost (Mills/Kw-Hr) | .72675 | .76855 | .71902 | .91011 |
| Net Capital Cost ($\$ \times 10^{-6}$) | 13.713 | 14.717 | 9.0020 | 15.726 |
| Turbine Exh. Temp. (F) | 139.3 | 136.3 | 140.3 | 140.2 |
| Air Side Frontal Area ($\text{Ft}^2 \times 10^{-6}$) | .34394 | .13264 | .227990 | .23077 |
| Water Temp. Drop (F) | 5.433 | 4.938 | 2.509 | 6/798 |
| Fan Power (KW) | | 16354 | 20664 | 22171 |
| Pump Power (KW) | | 515.6 | 323.8 | 140.8 |
| Total Water Flow Rate ($\text{lb/hr} \times 10^{-9}$) | 1.0203 | 1.0933 | .60966 | .80438 |
| Total Air Flow Rate ($\text{lb/hr} \times 10^{-9}$) | .42515 | .52708 | .63477 | .66838 |

TABLE XI (Cont.)

COMPARISON OF VARIOUS HEAT EXCHANGERS

| Surface | <u>Packed Bed</u> | <u>Finned Tube</u> | <u>Bare Glass Tubes</u> | |
|---|-------------------|--------------------|-------------------------|--------|
| Ratio of Heat Capacity of Water to That of Air | 9.9991 | 8.6429 | 4.0018 | 5.0156 |
| Length of Tubes (Ft) | 22.406 | 21.216 | 23.317 | 12.449 |
| Number of Tubes Deep | 3 | 10 | 13 | 12 |
| Number of Tubes Wide | 73679 | 24366 | 157122 | 296595 |

VIII. Conclusions and Recommendations

Most of the conclusions have already been reached in previous chapters. Some thermal plastics (especially rigid polyvinyl chloride) have been found to be satisfactory for use in dry cooling towers from a cost viewpoint. Others are more temperature resistant (i.e., polycarbonates) but more expensive. All require additional support, especially at higher temperatures, due to the effects of creep.

Thermoset materials, by themselves, show no particularly useful advantage over these thermoplastics as materials for dry cooling towers, and are more expensive to fabricate due to the need for a curing time.

Glass fiber reinforced plastics are more expensive yet are much stronger than pure plastics. This strength, however, degrades rapidly in the presence of hot water and modest loading. Hot water loosens the glass-plastic interface and flexural loading causes cracks to form in the plastic.

Pure glass tubes have a distinct advantage over all of the above materials in that they already have a thermal conductivity (0.5 BTU/HR-FT-F) adequate for dry cooling tower applications while the plastic materials must have fillers such as graphite or aluminum powder added. Glass is more fragile than the plastic materials but very inexpensive.

In a forced draft dry cooling tower, these materials are likely to be reasonably competitive with finned tube and packed bed designs depending on relative construction and material costs, interest charges, and thermal efficiencies.

The arbitrary nature of the computer program with regard to minimum air side pressure drop is of questionable value since it is based on the desire to minimize (or overcome) the effects of wind on a forced draft, dry cooling tower. This can be seen by referring to the present practice of the Rugeley, England, natural draft cooling towers whereby wind effects are minimized by using only those tower sectors which are not adversely affected by the wind. This artificial computer program constraint may well be masking a less costly system.

The computer program (as modified by this work) should be further refined to allow natural draft cooling tower calculations. In view of the practicality of using sector operation, this may be done without the complication introduced by attempting to counter the effects of wind.

Simplified manifolds for small diameter tubes should be developed such that preassembly of tubes may be accomplished at the factory on a production line. The quality control and relatively complex design imposed upon present chemical industry glass heat exchangers, for example, is quite excessive in terms of dry cooling tower requirements. It is likely that an assembly of scores of tubes could be joined to plastic tube sheets via a silicon rubber seal. The low pressures found in dry cooling towers make molded plastic manifolds a possibility.

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APPENDIX A
COMPUTER PROGRAM


```

DIMENSION PCST(8),TPER(8),TA(8)
COMMON VAR(5),VAL(5),VAS(5),TPO(4),TCOS1,CCOS1,REAL1,N1,HRFAL,W31,
1W41,U1,DEPW1,DEPA1,PPOW1,PCOS1,COSM1,DEFCL,WIDT1,ELEN1,VAIR1
2,VWAT1,H11,H01,T41,EFF1,QIN1,CBOIL,REWAL,NW1,TCOS,CCOS,REAIR,N,H
3RFAC,W3,W4,U,DELPW,DELPA,PPOW,FPOW,PCOS,COSM,DELFC,WIDTH,ELENG,VAI
4P,VWAT,HI,H0,T4,EFF,QIN,CBOIL,REWAT,NW,TEFF,PSIZE,PWCOS,PER,FCO
5S,FCR,CAPE
COMMON BCOST,HPCST,EFFP,EFFF,PROPC,FANV,RECOV,C1,C2,C3,C4,C5,XW,XD
1,DEQ,DD,CONF,AETR,ALPHA,SIGMA,SAC,SAS,DFIN,THFIN,BEDIA,CAF,TD,QREJ
2,XDEPA,KCONV,FAC,FAS
COMMON WALL,TCDIS,TCCON,VOLDIS,TCEQ,TCN
READ(5,75)(TA(I),I=1,8),(TPER(I),I=1,8)
READ(5,77)PSIZE,FCOS,PWCOS,BCOST,HPCST,PER,CAPE,FCR
READ(5,77)TEFF,EFFP,EFFF,PROPC,FANV,XDEPA,RECOV
READ(5,77)(TPO(I),I=1,4)
READ(5,76)C1,C2,C3,C4,C5
READ(5,77)XW,XD,DEQ,DD,CONF,AETR,ALPHA,SIGMA
READ(5,77)FAC,FAS,SAC,SAS,DFIN,THFIN,BEDIA
READ(5,10)WALL,TCDIS,TCCON,VOLDIS,TCEQ
WRITE(6,77)PSIZE,FCOS,PWCOS,BCOST,HPCST,PER,CAPE,FCR
WRITE(6,77)TEFF,EFFP,EFFF,PROPC,FANV,XDEPA,RECOV
WRITE(6,77)TPO(1),TPO(2),TPO(3),TPO(4)
WRITE(6,76)C1,C2,C3,C4,C5
WRITE(6,77)XW,XD,DEQ,DD,CONF,AETR,ALPHA,SIGMA
WRITE(6,77)FAC,FAS,SAC,SAS,DFIN,THFIN,BEDIA
WRITE(6,10)WALL,TCDIS,TCCON,VOLDIS,TCEQ
75 FORMAT(16F5.4)
76 FORMAT(8E10.3)
77 FORMAT(2F10.4)
10 FORMAT(5F10.5)
CRF=.5
C1=C1*CRF
C2=C2*CRF
C3=C3*CRF
C4=C4*CRF
C5=C5*CRF

```



```

DO 7 IS=1,5
7  VAR(IS)=0.0
   TCN=0.0
   TD= 60.
1  WRITE(6,81)TD
81  FORMAT(' TD USED IN THE FOLLOWING CALCULATIONS IS ='F8.3)
   K=4
   VAS(1)=135.
   VAS(3)=7.
   VAS(4)=2.E5
   VAS(5)=50.
4  CALL SHOT(1)
   IF(TCOS1.GT.0.0) GO TO 5
   VAS(4)=VAS(4)/4.
   GO TO 4
5  L=0
   CALL XTEND(L)
   IF(L.EQ.1) GO TO 4
   CALL SHOT(2)
2  CALL SERCH
   WRITE(6,82)CCOS1,TCOS1,VAR(2),EFF1,VAR(4),VAR(5)
82  FORMAT(' CCOS='E15.5,' TCOS='E15.5,' RANGE='F6.3,' EFF='F7.4,
1'  AFON='E15.5,' WLRT='F8.3)
   WRITE(6,83)REVAL,REAL1,N1,NW1,HRFAL,W31,W41
83  FORMAT(' PEWAT='F9.0,' REAIR='F9.0,' N='I5,' NW='I7,' HRFAC='
1F7.4,' W3='E15.5,' W4='E15.5)
   WRITE(6,84)U1,DEPW1,DEPA1,PPQW1,FPCW1,CBQ11
84  FORMAT(' U='F10.3,' DELPW='F10.3,' DELPA='F10.3,' PPQW='F10.3,
1'  FPCW='F10.3,' CBQ11='E12.5)
   WRITE(6,85)CCOS1,COSM1,DEFC1,T41,VAR(3),BEDIA
85  FORMAT(' CCOS='E15.5,' COSM='E15.5,' DELFC='E15.5,' T4='F8.3,
1'  CWAPA='F7.4,' BEDIA='F5.3)
   WRITE(6,86)VAIP1,VWAT1,HQ1,H11,WIDT1,ELEN1,VAR(1)
86  FORMAT(' VAIR='F10.3,' VWAT='F10.3,' HAIR='F10.3,' HWAT='F10.3,
1'  WIDTH='F10.3,' LENGTH='F10.3,' T1='F7.3)
   K=K-1

```



```

IF(K.GT.0) GO TO 2
DO 3 I=1,8
3 CALL VARIT(TA(I),TPER(I),PCST(I))
ACOS=PCST(1)+PCST(2)+PCST(3)+PCST(4)+PCST(5)+PCST(6)+PCST(7)+PCST(
18)
WRITE(6,87)ACOS
87 FORMAT(' ACOS='E15.5)
TD=TD+5.
IF(TD.LE.100.) GO TO 1
STOP
END

```

```

MAIN0073
MAIN0074
MAIN0075
MAIN0076
MAIN0077
MAIN0078
MAIN0079
MAIN0080
MAIN0081
MAIN0082
MAIN0083

```



```

SUBROUTINE SHOT(L)
  DIMENSION T(3), CWAR(4), RANG(3), AFRO(3), WLR(4), VAM(5)
  COMMON VAR(5), VAL(5), VAS(5), TPO(4), TCOS1, CCOS1, REAI1, NL, HRFAL, W31,
1W41, U1, DEPW1, DEPA1, PPQW1, FPOW1, CCOS1, CCOS1, DEFC1, WIDT1, ELENI, VAIR1
2, VWAT1, HI1, HO1, T41, EFF1, QIN1, CRCI1, REWAL, NW1, TCOS, CCCS, REAIR, N, H
3REAC, W3, W4, U, DELPW, DELPA, PPOW, FPOW, OCCS, COSM, DELEFC, WIDTH, ELENG, VAI
4R, VWAT, HI, HQ, T4, EFF, QIN, CRCI1, REWAT, NW, TEFF, PSIZE, PWCOS, PER, FCO
5S, FCR, CAPF
  COMMON RCOST, HPCST, EFPF, EFFF, PROPC, FANV, PECCV, C1, C2, C3, C4, C5, XW, XD
1, DEQ, QD, CONF, AFR, ALPHA, SIGMA, SAC, SAS, DFIN, THFIN, REDIA, CAF, TD, QREJ
2, XDEPA, KCONV, FAC, FAS
  COMMON WALL, TCDIS, TCCCN, VOLDIS, TCEQ, TCN
  IF(L.EQ.2) GO TO 31
  TCOS1=0.
  TCOS2=0.
  DO 20 I=1,3
    T(I)=VAS(I)+(I-2)*5.
  IF(T(I).GE.170.) T(I)=170.
20 IF(T(I).LE.100.) T(I)=110.
  DO 21 I=1,4
    CWAR(I)=VAS(3)+(I-2)*2.
21 IF(CWAR(I).LE.0.) CWAR(I)=.5
  DO 22 I=1,4
    WLR(I)=VAS(5)+(I-2)*10.
22 IF(WLR(I).LE.0.) WLR(I)=5.
  AFRO(1)=VAS(4)/2.
  AFRO(2)=VAS(4)
  AFRO(3)=VAS(4)*2.
  DT1=1.
  DCWAR=1.
  DAFRO=1.
  DWLRA=1.
  LC=4
  LW=4
  GO TO 51
31 DT1=VAR(1)-VAM(1)

```



```

DCWAR=VAR(3)-VAM(3)
DAFRO=VAR(4)-VAM(4)
DWLRA=VAR(5)-VAM(5)
IF(DT1.EQ.0.) GO TO 33
DO 32 I=1,3
32 T(I)=VAR(1)-(I-1)*DT1/2.
GO TO 35
33 DO 34 I=1,3
T(I)=VAR(1)+(I-2)*2.
34 IF(T(I).GE.170.) T(I)=170.
35 IF(DCWAR.EQ.0.) GO TO 37
DO 36 I=1,4
36 CWAR(I)=VAR(3)-(I-1)*DCWAR/3.
GO TO 39
37 DO 38 I=1,3
38 CWAR(I)=VAP(3)+(I-2)
LC=3
39 IF(DAFRO.EQ.0.) GO TO 41
DO 40 I=1,3
40 AFRO(I)=VAR(4)-(I-1)*DAFRO/2.
GO TO 43
41 DO 42 I=1,3
42 AFRO(I)=VAR(4)+(I-2)*.5E5
43 IF(DWLRA.EQ.0.) GO TO 45
DO 44 I=1,4
44 WLRA(I)=VAR(5)-(I-1)*DWLRA/3.
GO TO 51
45 DO 46 I=1,3
46 WLRA(I)=VAP(5)+(I-2)*5.
LW=3
51 DO 15 IT=1,3
DO 15 IC=1,LC
IF(CWAR(IC).GE.1.) GO TO 1
RANGL=(1.-EXP(-CWAR(IC)))*(T(IT)-TD)/CWAR(IC)
GO TO 2
1 RANGL=(1.-EXP(-1./CWAR(IC)))*(T(IT)-TD)

```

PAGE 5


```

2  RANG(1)=.0*RANGL
   RANG(2)=.7*RANGL
   RANG(3)=.5*RANGL
   DO 15 IR=1,3
   DO 15 IA=1,3
   DO 15 IW=1,LW
      KCALC=1
      IF(IR.GT.1.OR.IC.GT.1) KCALC=2
      IF(IA.GT.1) KCALC=4
      IF(IW.GT.1) KCALC=5
      CALL CALC(T(IT),RANG(IR),CWAR(IC),AFPO(IA),WLRA(IW),KCALC)
      IF(KCONV.EQ.1) GO TO 15
      IF(DELPA.LT.XDEPA) GO TO 16
      IF(TCOS1.EQ.0.) GO TO 14
      IF(TCOS.GT.TCOS1) GO TO 15
      GO TO 14
16  IF(L.EQ.2) GO TO 15
      IF(TCOS2.EQ.0.) GO TO 17
      IF(TCOS.GT.TCOS2) GO TO 15
17  TCOS2=TCOS
      VAM(1)=T(IT)
      VAM(3)=CWAR(IC)
      VAM(4)=AFPO(IA)
      VAM(5)=WLRA(IW)
      GO TO 15
14  TCOS1=TCOS
      VAR(1)=T(IT)
      VAR(2)=RANG(IR)
      VAR(3)=CWAR(IC)
      VAR(4)=AFPO(IA)
      VAR(5)=WLRA(IW)
      CAF=AFPO(1)*.1
15  CONTINUE
      WRITE(6,553)TCOS1,VAR(1),VAR(2),VAR(3),VAR(4),VAR(5)
553  FORMAT(' TCOS1=E12.5,' T11=F4.0,' RANG1=F7.4,' CWAR1=F7.3,
1' AFRQ1=E10.3,' WLRA1=F4.0)

```


SHOT0109
SHOT0110

RETURN
END

PAGE 7


```

SUBROUTINE XTEND(L)
  DIMENSION TTRY(2),RTRY(2),CTRY(2),ATRY(2),WTRY(2)
  COMMON VAR(5),VAL(5),VAS(5),TPQ(4),TCOS1,CCOS1,REAL1,N1,HRFAL,W31,
1W41,U1,DEPW1,DEPA1,PPOW1,FPOW1,OCOS1,CCSM1,DEFC1,WIDT1,ELEN1,VAIR1
2,VWAT1,H11,H01,T41,EFF1,QIN1,CPO11,REWAL,NW1,TCOS,CCCS,REAIR,N,H
3RFAC,W3,W4,U,DELPW,DELPA,PPOW,FPOW,CCCS,COSM,DELFC,WIDTH,ELENG,VAI
4R,VNAT,HI,H0,T4,EFF,QIN,CBOIL,REWAT,NW,TEFF,PSIZE,PWCOS,PER,FCO
5S,FCR,CAPE
  COMMON BCOST,HPCST,EFFP,EFFF,PROPC,FANV,RECOV,C1,C2,C3,C4,C5,XW,XD
1,DEQ,OD,CONF,AFTR,ALPHA,SIGMA,SAC,SAS,DFIN,THFIN,REDIA,CAF,TD,QREJ
2,XDEPA,KCCNV,FAC,FAS
  COMMON WALL,TCDIS,TCCON,VOLDIS,TCEQ,TCN
  TTRY(1)=VAR(1)-20.
  IF(TTRY(1).LE.100.) TTRY(1)=110.
  TTRY(2)=VAR(1)+20.
  IF(TTRY(2).GE.170.) TTRY(2)=170.
  CTRY(1)=VAR(3)-3.
  IF(CTRY(1).LE.0.) CTRY(1)=.5
  CTRY(2)=VAR(3)+2.
  ATRY(1)=VAP(4)*4.
  ATRY(2)=VAP(4)/4.
  WTRY(1)=VAR(5)+40.
  WTRY(2)=VAP(5)/3.
  DO 3 I=1,2
  IF(VAR(3).GE.1.) GO TO 1
  RANGL=(1.-EXP(-VAR(3)))*(TTRY(1)-TD)/VAR(3)
  GO TO 2
1 RANGL=(1.-EXP(-1./VAR(3)))*(TTRY(1)-TD)
2 RTRY(1)=.9*RANGL
  RTRY(2)=.7*RANGL
  DO 3 IR=1,2
  CALL CALC(TTRY(1),RTRY(1R),VAR(3),VAR(4),VAR(5),1)
  IF(DELPA.LT.XDEPA) GO TO 3
  IF(TCOS.GT..99*TCOS1) GO TO 3
  TCOS1=TCOS
  VAS(1)=TTRY(1)

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XTEN0001
 XTEN0002
 XTEN0003
 XTEN0004
 XTEN0005
 XTEN0006
 XTEN0007
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XTEN0037
XTEN0038
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XTEN0042
XTEN0043
XTEN0044
XTEN0045
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XTEN0050
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XTEN0055
XTEN0056
XTEN0057
XTEN0058
XTEN0059
XTEN0060
XTEN0061
XTEN0062
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XTEN0064
XTEN0065
XTEN0066
XTEN0067
XTEN0068
XTEN0069
XTEN0070
XTEN0071
XTEN0072

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VAS(3)=VAR(3)
VAS(4)=VAR(4)
VAS(5)=VAR(5)
L=1
3 CONTINUE
DO 10 I=1,2
IF(CTRY(I).GE.1.) GO TO 8
RANGL=(1.-EXP(-CTRY(I)))*(VAR(1)-TD)/CTRY(I)
GO TO 9
8 RANGL=(1.-EXP(-1./CTRY(I)))*(VAR(1)-TD)
9 RTRY(1)=.9*RANGL
RTRY(2)=.7*RANGL
DO 10 IR=1,2
CALL CALC(VAR(1),RTRY(IR),CTRY(I),VAR(4),VAR(5),I)
IF(DELPA.LT.XDEPA) GO TO 10
IF(TCOS.GT..99*TCOS1) GO TO 10
TCOS1=TCOS
VAS(1)=VAR(1)
VAS(3)=CTRY(I)
VAS(4)=VAR(4)
VAS(5)=VAR(5)
L=1
10 CONTINUE
DO 11 I=1,2
CALL CALC(VAR(1),VAR(2),VAR(3),ATRY(I),VAR(5),2*I)
IF(DELPA.LT.XDEPA) GO TO 11
IF(TCOS.GT..99*TCOS1) GO TO 11
TCOS1=TCOS
VAS(1)=VAR(1)
VAS(3)=VAR(3)
VAS(4)=ATRY(I)
VAS(5)=VAR(5)
L=1
11 CONTINUE
DO 12 I=1,2
CALL CALC(VAR(1),VAR(2),VAR(3),VAR(4),WTRY(I),3+I)

```



```

IF(DELPA.LT.XDEPA) GO TO 12
IF(TCOS.GT..99*TCOS1) GO TO 12
TCOS1=TCOS
VAS(1)=VAR(1)
VAS(3)=VAR(3)
VAS(4)=VAR(4)
VAS(5)=WTRY(1)
L=1
12 CONTINUE
IF(L.EQ.1) WRITE(6,13)
13 FORMAT(' XTEND CALLED, AND CHANGE MADE')
RETURN
END

```

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XTEN00073
XTEN00074
XTEN00075
XTEN00076
XTEN00077
XTEN00078
XTEN00079
XTEN00080
XTEN00081
XTEN00082
XTEN00083
XTEN00084
XTEN00085

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SUBROUTINE SERCH
  DIMENSION C(5)
  COMMON VAR(5), VAL(5), VAS(5), TPO(4), TCOS1, CCOS1, REAIL, N1, HRFAL, W31,
1W41, U1, DEPW1, DEPA1, PPOW1, FPOW1, OCOS1, CCOS1, DEFC1, WIDT1, ELEN1, VAIR1
2, VWAT1, H11, H01, T41, EFF1, QIN1, CBO11, REWAL, NW1, TCOS, CCCS, REAIR, N, H
3RFAC, W3, W4, U, DELPW, DELPA, PPOW, FPOW, PCOS, COSM, DELFC, WIDTH, ELENG, VAI
4R, VWAT, H1, H0, T4, EFF, QIN, CROIL, REWAT, NW, TEFF, PSIZE, PWCOS, PER, FCO
5S, FCR, CAF
  COMMON BCOST, HPCST, EFFP, EFFF, PROPC, FANV, RECOV, C1, C2, C3, C4, C5, XW, XD
1, DEQ, QD, CONF, AFTR, ALPHA, SIGMA, SAC, SAS, DFIN, THFIN, BEDIA, CAF, TD, QREJ
2, XDEPA, KCONV, FAC, FAS
  COMMON WALL, TCDIS, TCCON, VOLDIS, TCEQ, TCN
  C(1)=5.
  C(2)=1.
  C(3)=1.
  C(4)=CAF
  C(5)=5.
  DO 8 I=1,5
    M=6-I
    K=3
    DO 9 IK=1,5
      VAL(IK)=VAP(IK)
      L=1
      KC=0
      J=0
      1 VAL(M)=VAR(M)+C(M)
      IF(M.NE.2) GO TO 10
      IF(VAL(3).GE.1.) GO TO 60
      RANGL=(1.-EXP(-VAL(3)))*(VAL(1)-TD)/VAL(3)
      GO TO 51
      60 RANGL=(1.-EXP(-1./VAL(3)))*(VAL(1)-TD)
      61 IF(VAL(2).GE.RANGL) GO TO 4
      10 IF(VAL(1).GT.170.) GO TO 4
      IF(VAL(3).GE.-1./ALOG(1.-VAL(2)/(VAL(1)-TD))) GO TO 4
      CALL CALC(VAL(1),VAL(2),VAL(3),VAL(4),VAL(5),L)
      L=M

```

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IF(DELPA.LT.XDEPA) GO TO 3
IF(TCOS.GT.TCOS1) GO TO 4
J=1
CALL STORE
GO TO 2
3 IF(K.EQ.1) KC=1
4 IF(J.EQ.1) GO TO 7
5 VAL(M)=VAR(M)-C(M)
IF(VAL(M).LE.0.0) GO TO 7
IF(VAL(1).LE.TD+VAL(2)/(1.-EXP(-1./VAL(3))).OR.VAL(1).LT.110.) GO
  1 TO 7
CALL CALC(VAL(1),VAL(2),VAL(3),VAL(4),VAL(5),M)
IF(DELPA.LT.XDEPA) GO TO 6
IF(TCOS.GT.TCOS1) GO TO 7
CALL STORE
KC=0
GO TO 5
6 IF(K.EQ.1) KC=1
7 IF(KC.EQ.1) CALL CHNGE(M)
K=K-1
WRITE(6,18)K,M,VAR(M),M,VAL(M),TCOS,TCOS1,DELPA
18 FORMAT(' K=',I2,' VAR(',I1,')='E15.5,' VAL(',I1,')='E15.5,' TCOS=',
  1E15.5,' TCOS1='E15.5,' DELPA='F10.6)
IF(K.EQ.0) GO TO 8
C(M)=C(M)/5.
GO TO 1
8 CONTINUE
RETURN
END

```



```

SUBROUTINE CHNGE(M)
  DIMENSION DP(5),DV(5),VAS(5),VAJ(5)
  COMMON VAR(5),DEPA1,DEPA2,PPOW1,PPOW2,DEFCL,WIDT1,ELEN1,VAIR1
1W41,U1,DEPW1,DEPA1,PPOW1,PPOW2,DEFCL,WIDT1,ELEN1,VAIR1
2,VWAT1,HI1,HO1,T41,EFF1,QIN1,CRCI1,REWA1,NW1,TCOS,CCOS,REAIR,N,H
3RFAC,W3,W4,U,DELPW,DELPA,PPOW,FPOW,CCOS,CCSM,DELFC,WIDTH,ELENG,VAI
4R,VWAT,HI,HO,T4,EFF,QIN,CRCI1,REWA1,NW,TEFF,PSIZE,PWCOS,PER,FCO
5S,FCP,CAPE
  COMMON BCOST,HPCST,EFFP,EFFF,PROPC,FANV,RECOV,C1,C2,C3,C4,C5,XN,XD
1,DEQ,QD,CONF,AETR,ALPHA,SIGMA,SAC,SAS,DFIN,THFIN,REDIA,CAF,TD,QREJ
2,XDEPA,KCONV,FAC,FAS
  COMMON WALL,TCDIS,TCCON,VOLDIS,TCEQ,TCN
  WRITE(6,100)
100 FORMAT(' SUBROUTINE CHNGE CALLED')
  L=0
  K1=0
  DO 1 I=1,3
1  DV(I)=.05
  DO 2 I=1,2
2  DV(I+3)=.2
  DO 3 I=1,5
3  VAJ(I)=VAR(I)
4  VAL(I)=VAR(I)
  VAL(M)=(1.+DV(M))*VAR(M)
  IF(VAL(M).LE.0.0) GO TO 36
  IF(M.GT.3) GO TO 10
  IF(M-2)5,6,9
5  IF(VAL(1).GE.170.) GO TO 36
  IF(VAL(1).LE.TD+VAL(2)/(1.-EXP(-1./VAL(3))).OR.VAL(1).LT.110.) GO
  1 TO 36
  GO TO 10
6  IF(VAL(3).GE.1.) GO TO 7
  RANGL=(1.-EXP(-VAL(3)))*(VAL(1)-TD)/VAL(3)
  GO TO 8
7  RANGL=(1.-EXP(-1./VAL(3)))*(VAL(1)-TD)
8  IF(VAL(2).GE.RANGL) GO TO 36

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```

GO TO 10
9 IF (VAL(3).GE.-1./ALOG(1.-VAL(2)/(VAL(1)-TD))) GO TO 36
10 CALL CALC(VAL(1),VAL(2),VAL(3),VAL(4),VAL(5),1)
IF (KCONV.EQ.1) GO TO 36
DP(M)=DELP A-DEPAI
DO 35 II=1,5
I=6-II
IF (I.EQ.5.AND.DV(1).GT..005) GO TO 35
IF (I.EQ.M) GO TO 35
11 VAL(I)=(1.+DV(I))*VAR(I)
IF (VAL(I).LE.0.0) GO TO 34
IF (I.GT.3) GO TO 17
IF (I-2) 12,13,16
12 IF (VAL(1).GE.170.) GO TO 34
IF (VAL(1).LE.TD+VAR(2)/(1.-EXP(-1./VAR(3))).OR.VAL(1).LT.110.) GO
1 TO 34
GO TO 17
13 IF (VAR(3).GE.1.) GO TO 14
RANGL=(1.-EXP(-VAR(3)))*(VAF(1)-TD)/VAR(3)
GO TO 15
14 RANGL=(1.-EXP(-1./VAR(3)))*(VAR(1)-TD)
15 IF (VAL(2).GE.RANGL) GO TO 34
GO TO 17
16 IF (VAL(3).GE.-1./ALOG(1.-VAR(2)/(VAR(1)-TD))) GO TO 34
17 VAJ(I)=VAL(I)
J=I
IF (M.LT.I) J=M
CALL CALC(VAJ(1),VAJ(2),VAJ(3),VAJ(4),VAJ(5),J)
VAJ(I)=VAR(I)
IF (KCONV.EQ.1) GO TO 34
DP(I)=DELP A-DEPAI
E=0.
C=1.
D=1.
18 VAL(I)=(1.+DV(I))*(E-DP(M))/DP(I)*VAR(I)
IF (VAL(I).LE.0.0) GO TO 34

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CHNG0037
CHNG0038
CHNG0039
CHNG0040
CHNG0041
CHNG0042
CHNG0043
CHNG0044
CHNG0045
CHNG0046
CHNG0047
CHNG0048
CHNG0049
CHNG0050
CHNG0051
CHNG0052
CHNG0053
CHNG0054
CHNG0055
CHNG0056
CHNG0057
CHNG0058
CHNG0059
CHNG0060
CHNG0061
CHNG0062
CHNG0063
CHNG0064
CHNG0065
CHNG0066
CHNG0067
CHNG0068
CHNG0069
CHNG0070
CHNG0071
CHNG0072


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IF(I.GT.3) GO TO 24
IF(I-2) 19,20,23
19 IF(VA(1).GE.170.) GO TO 34
IF(VA(1).LE.TD+VA(2)/(1.-EXP(-1./VA(3))),OR.VA(1).LT.110.) GO
1 TO 34
GO TO 24
20 IF(VA(3).GE.1.) GO TO 21
RANGL=(1.-EXP(-VA(3)))*(VA(1)-TD)/VA(3)
GO TO 22
21 RANGL=(1.-EXP(-1./VA(3)))*(VA(1)-TD)
22 IF(VA(2).GE.RANGL) GO TO 34
GO TO 24
23 IF(VA(3).GE.-1./ALOG(1.-VA(2)/(VA(1)-TD))) GO TO 34
24 CALL CALC(VA(1),VA(2),VA(3),VA(4),VA(5),J)
IF(KCONV.EQ.1) GO TO 34
IF(DELPA.GE.XDEPA.AND.DELPA.LE.1.01*XDEPA) GO TO 26
IF(DELPA.GE.1.01*XDEPA) GO TO 25
C=D/10.
IF(C.LT..001) GO TO 34
E=E+C
GO TO 13
25 D=C/10.
IF(D.LT..001) GO TO 34
E=E-D
GO TO 18
26 IF(TCOS.GT.TCOS1) GO TO 34
CALL STORE
L=1
DO 27 IJ=1,5
27 VAJ(IJ)=VAR(IJ)
VA(M)=(1.+DV(M))*VAR(M)
IF(VA(M).LE.0.0) GO TO 36
IF(M.GT.3) GO TO 33
IF(M-2) 28,29,32
28 IF(VA(1).GE.170.) GO TO 36
IF(VA(1).LE.TD+VA(2)/(1.-EXP(-1./VA(3))),OR.VA(1).LT.110.) GO

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1 TO 36
GO TO 33
29 IF (VAL(3).GE.1.) GO TO 30
   RANGL=(1.-EXP(-VAL(3)))*(VAL(1)-TD)/VAL(3)
   GO TO 31
30 RANGL=(1.-EXP(-1./VAL(3)))*(VAL(1)-TD)
31 IF (VAL(2).GE.RANGL) GO TO 36
   GO TO 33
32 IF (VAL(3).GE.-1./ALOG(1.-VAL(2)/(VAL(1)-TD))) GO TO 36
33 CALL CALC(VAL(1),VAL(2),VAL(3),VAL(4),VAL(5),M)
   IF (KCONV.EQ.1) GO TO 36
   DP(M)=DELP A-DEPA1
   GO TO 11
34 VAL(1)=VAR(I)
35 CONTINUE
36 DO 37 I=1,5
37 DV(I)=-DV(I)
   K1=K1+1
   IF (K1.EQ.1) GO TO 4
   K1=0
   IF (DV(1).LE..005) GO TO 39
   DO 38 I=1,5
38 DV(I)=DV(I)/5.
   GO TO 4
39 IF (L.EQ.1) WRITE(6,103)
103 FORMAT('          AND CHANGES MADE')
   RETURN
   END
CHNG0109
CHNG0110
CHNG0111
CHNG0112
CHNG0113
CHNG0114
CHNG0115
CHNG0116
CHNG0117
CHNG0118
CHNG0119
CHNG0120
CHNG0121
CHNG0122
CHNG0123
CHNG0124
CHNG0125
CHNG0126
CHNG0127
CHNG0128
CHNG0129
CHNG0130
CHNG0131
CHNG0132
CHNG0133
CHNG0134
CHNG0135
CHNG0136

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SUBROUTINE CALC(T1,RANGE,CWARA,AFRCN,WLPAT,M)
COMMON VAR(5),VAL(5),VAS(5),TPO(4),TCCS1,CCOS1,REAI1,N1,HREFAI,W31,
1W41,U1,DEPW1,DEPA1,PPON1,FPOW1,OCOS1,COSM1,DEFC1,WIDT1,ELEN1,VAIR1
2,VWAT1,H11,H01,T41,EFF1,QIN1,CBOIL,REWAT,NW1 ,TCOS,CCCS,REAIR,N,H
3RFAC,W3,W4,U,DELPW,DELPA,PPQW,FPQW,QCOS,COSM,DELFC,WIDTH,ELENG,VAI
4R,VWAT,HI,H0,T4,EFF,QIN,CBOIL,REWAT,NW ,TEFF,PSIZE,PWCOS,PER,FCO
5S,FCR,CAPE
COMMON BCOST,HPCST,EFFP,EFFF,PROPC,FANV,RECON,C1,C2,C3,C4,C5,XW,XD
1,DEQ,OD,CONF,AFTR,ALPHA,SIGMA,SAC,SAS,DFIN,THFIN,BEDIA,CAF,TD,QREJ
2,XDEPA,KCONV,FAC,FAS
COMMON WALL, TCDIS,TCCON,VOLDIS,TCEQ, TCN
KCONV=0
IF(M.EQ.5) GO TO 23
IF(M.EQ.4) GO TO 22
IF(M.EQ.3) GO TO 21
IF(M.EQ.2) GO TO 20
P=EXP(17.168-9240./(T1+460.))
HREFAC=TPO(1)+TPO(2)*P+TPO(3)*P**2+TPO(4)*P**3
TEFFM=TEFF/HREFAC
QIN=3413.*PSIZE*1000./TEFFM
QREJ=QIN*(1.-TEFFM)
20 W3=QREJ/RANGE
21 W4=W3/(CWARA*.24)
IF(CWARA.GE.1.) GO TO 1
EFF=RANGE/(T1-TD)
CRAT=CWARA
CMIN=W3
GO TO 2
1 EFF=CWARA*RANGE/(T1-TD)
CRAT=1./CWARA
CMIN=.24*W4
2 ANTJ=-ALOG((1./CRAT)*ALOG(1.-CRAT*EFF)+1.)
22 GAIR=W4/(AFRCN*SIGMA)
VAIP=GAIR/(.073*3600.)
REAIR=DEQ*GAIP/.046
STPR=SAC/(REAIR**SAS)

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CALC0001
 CALC0002
 CALC0003
 CALC0004
 CALC0005
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 CALC0030
 CALC0031
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 CALC0033
 CALC0034
 CALC0035
 CALC0036


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FAIR=FAC/(REAIR**FAS)
HO=STPR*GAIR*.24/.793
IF(BEDIA.NE.0.0) GO TO 3
IF(THFIN.EQ.0.0) GO TO 23
BFIN=(DFIN/OD+4./3.)/7.
EFFIN=1./((1.+(BFIN*HO*(DFIN-OD)**2)/(24.*CONF*THFIN))
GO TO 4
3 BFIN=SQRT(144.*HO/(CONF*BEDIA))
EFFIN=TANH(BFIN*BEDIA/4.)/(BFIN*BEDIA/4.)
4 EFS=1.-AFTR*(1.-EFFIN)
23 WIDTH=SQRT(WLPAT*AFRON)
NW=WIDTH/XW*12
KN=0
N=2
5 REWAT=48.*W3/(3.14*1.65*CD*N*NW)
HI=.1836*(REWAT**.8)/OD
CALL TCLOW
CHECK=TCCON+TCFQ
IF(CHECK.EQ.0.0) GO TO 7
GO TO 8
7 U=1./((1./(EFS*HO)+1./((1.-AFTR)*HI))
8 AAIR=ANTU*CMIN/U
TCN=1.0
VCL=AAIR/ALPHA
DEPTH=VCL/AFRON
ND=DEPTH/XD*12
NDEL=N-ND
IF(NDEL*NDEL.LT.1) GO TO 11
KN=KN+1
IF(KN.GT.4) GO TO 10
IF(ND.LT.1) GO TO 9
N=ND
GO TO 5
9 N=1
GO TO 5
10 WRITE(6,80)N,ND

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80 FORMAT(' TUBE BANKS NOT CONVERGENT, WITH N=',I6,' AND ND=',I6)
   KCONV=1
11 GWAT=576.*W3/(3.14*OD*OD*N*NW)
   VWAT=GWAT/(62.*3600.)
   ELENG=WIDTH/WLRAT
   IF(REWAT.GT.2000.) GO TO 12
   FWAT=16./REWAT
   GO TO 14
12 IF(REWAT.GT.1.F5) GO TO 13
   FWAT=.0791/(REWAT**.25)
   GO TO 14
13 FWAT=.046/(REWAT**.2)
14 DELPW=48.*FWAT*ELENG*(GWAT/ 3600.)**2/(OD*62.*64.4)
   T4=CWRA*ARANGE+TD
   AV4AP=(T4+460.)/(TD+460.)
   AVMAR=(T4+TD)/2.+460.)/(TD+460.)
   VA=53.35*(TD+460.)/(15.*144.)
   AFACT=(1.+SIGMA**2)*(AV4AP-1.)+FAIR*DEPTH*4.*AVMAR/DEQ
   DELPA=(GAIR/3600.)**2*VA*AFAC/64.4
   HPWAT=DELPW*W3/(62.*3600.*550.)
   PPQW=HPWAT/(1.341*EFFP)
   HPAIR=W4*(DELPA*VA+VAIR**2/(64.4*(1.-RECOV)))/(3600.*550.)
   FPQW=HPAIR/(1.341*EFFE)
   ATUB=(1.-AFTR)*AAIR
   XN=N
   CPERA=C1+C2*XN+C3*XN**2+C4*XN**3+C5*XN**4
   CBOIL=(HRFAC-1.)*BCOST*1.E6
   CQCS=ATUB*CPERA+(HPWAT+HPAIR)*HPCST+VAIR*AFRON*PROPC/FANV
   OQCS=(PPQW+FPQW)/(PSIZE*1000.)*PWCCS
   DELFC=EQCS*3413.*(HRFAC-1.)/TEFF*1.E-5
   COSM=CQCS*PER/(PSIZE*CAPF*8760.)
   TCQS=(CQCS+CBOIL)*FCR/(PSIZE*1000.*CAPF*8.76)+QCS+COSM+DELFC
   RETURN
   END

```



```

SUBROUTINE VARIIT(TA,TPER,PCST)
COMMON VAR(5),VAL(5),VAS(5),TPQ(4),TCOS1,CCOS1,REAI1,N1,HRFAC,W31,
1W41,U1,DEPW1,DEPA1,PPOW1,FPOW1,OCOS1,CCSM1,DEFC1,WIDT1,ELEN1,VAIR1
2,VWAT1,H11,H01,T41,EFF1,QIN1,CBOI1,REWA1,NW1,DUM1,CCCS,REAIR,N,D
3UMY1,W3,W4,U,DELPW,DELPA,PPOW,FPOW,OCOS,CCSM,DUMY2,WIDTH,ELENG,VAI
4R,VWAT,H1,H0,T4,EFF,QIN,CBOIL,REWA,NW,TEFF,PSIZE,PWCOS,PER,FCQ
5S,FCR,CAPE
COMMON BCOST,HPCST,EFFP,EFFF,PROPC,FANV,RECOV,C1,C2,C3,C4,C5,XW,XD
1,DEQ,OD,CONF,AFT,ALPHA,SIGMA,SAC,SAS,DEFIN,THFIN,REDIA,CAF,TD,DUM2
2,XDEPA,KCONV,FAC,FAS
COMMON WALL,TCDIS,TCCON,VOLDIS,TCEQ,TCN
T1=140.
1 P=EXP(17.168-9240./(T1+460.))
HRFAC=TPQ(1)+TPQ(2)*P+TPQ(3)*P**2+TPQ(4)*P**3
TEFFM=TEFF/HRFAC
QREJ=QIN1*(1.-TEFFM)
RANGE=QREJ/W31
IF(VAR(3).GT.1.) GO TO 2
T11=RANGE/EFF1+TA
GO TO 3
2 T11=RANGE*VAR(3)/EFF1+TA
3 IF((T11-T1)**2.LE.1.) GO TO 4
T1=T11
GO TO 1
4 PGEN=QIN1*TEFFM/(3413.*1000.)
IF(PGEN.GE.PSIZE) GO TO 5
CSTCL=(PSIZE-PGEN)/PSIZE*PWCOS
GO TO 6
5 CSTCL=0
6 DELFC=FCOS*3413.*(HRFAC-1.)/TEFFM*1.E-5
TCOS=(CCOS1+CBOI1)*FCR/(PSIZE*CAPF*8760.)+OCOS1+CCSM1+DELFC+CSTCL
PCST=TPER*TCOS
WRITE(6,7)
7 FORMAT(' SUBROUTINE DATA')
WRITE(6,8)HRFAC,PGEN,CSTCL,DELFC
8 FORMAT(' HRFAC='F7.4,' PGEN='F8.3,' CSTCL='E15.5,' DELFC='E15.5)

```



```
WRITE(5,9) RANGE,TCOS,PCST,T11,TA
9 FORMAT(' RANGE='F6.3,' TCOS='E15.5,' PCST='E15.5,' T11='F7.3,
1' TA='F6.2)
RETURN
END
```

```
VARI0037
VARI0038
VARI0039
VARI0040
VARI0041
```



```

SUBROUTINE STORE
COMMON VAR(5),VAL(5),VAS(5),TPO(4),S(27),W(27),TEFF,PSIZE,PWCOS,PE
IR,FCOS,FCR,CAPF
COMMON BCOST,HPCST,EFFP,EFFF,PROPC,FANV,RECOV,C1,C2,C3,C4,C5,XW,XD
1,DEQ,QD,CONF,AETR,ALPHA,SIGMA,SAC,SAS,DFIN,THFIN,BEDIA,CAF,TD,QREJ
2,XDEPA,KCONV,FAC,FAS
COMMON WALL, TCDIS,TCCON,VOLDIS,TCEQ, TCN
DO 1 I=1,5
1 VAR(I)=VAL(I)
DO 2 I=1,27
2 S(I)=W(I)
RETURN
END

```

```

STOR0001
STOR0002
STOR0003
STOR0004
STOR0005
STOR0006
STOR0007
STOR0008
STOR0009
STOR0010
STOR0011
STOR0012
STOR0013

```



```

SUBROUTINE TCLOW
COMMON VAR(5),VAL(5),VAS(5),TPQ(4),TCOS1,CCOS1,REAI1,N1,HRFAL,W31,
1W41,U1,DEPW1,DEPA1,PPOW1,FPOW1,OCOS1,CCOS1,DEFCL,WIDT1,ELEN1,VAIR1
2,VWAT1,HI1,HQ1,T41,EFF1,QIN1,CBOI1,REWA1,NW1,TCOS,CCOS,REAIR,N,H
3RFAC,W3,W4,U,DELPW,DELPA,PPOW,FPOW,CCOS,CCSM,DELFC,WIDTH,ELENG,VAI
4R,VWAT,HI,HQ,T4,EFF,QIN,CBOIL,REWAT,NW,TEFF,PSIZE,PWCOS,PER,FCO
5S,FCR,CAPE
COMMON BCOST,HPCST,EFFP,EFFF,PROPC,FANV,RECOV,C1,C2,C3,C4,C5,XW,XD
1,DEO,DD,CONF,AFTR,ALPHA,SIGMA,SAC,SAS,DFIN,THFIN,BEDIA,CAF,TD,QREJ
2,XDEPA,KCONV,FAC,FAS
COMMON WALL,TCDIS,TCCON,VOLDIS,TCEQ,TCN
IF(TCEQ.NE.0.0) GO TO 4
IF(TCCON.EQ.0.0) GO TO 3
TCRAT=TCDIS/TCCON
IF(TCRAT.GT.100.) GO TO 2
CVRB= (3.*VOLDIS/2.)*0.5
CVRB=4.*(2./(3.*VOLDIS))*0.5
CVRI=((1.-CVRB)/TCCON)+(1.0/(CVRB*(TCDIS-TCCON))*(TCCON+CVRB*(TCDIS
1-TCCON)))*0.5)*ALOG(((TCCON+CVRB*(TCDIS-TCCON))*0.5+(CVRB*0.5)*(
2CVRB*(TCDIS-TCCON))*0.5)/((TCCON + CVRB*(TCDIS-TCCON))*0.5)-(CV
3RB*0.5)*(CVRB*(TCDIS-TCCON))*0.5))
TCEQ=1./CVRI
WRITE(6,50) TCEQ
50 FORMAT(' CALCULATED THERMAL CONDUCTIVITY OF THE COMPOSITE WALL IS
1 , F15.9)
4 RI=DD/24.-WALL/12.
RO = DD/24.
U=0.0
U=1./(1./HI+(RI/TCEQ)*ALOG(PO/RI))+RI/(RO*HQ))
GO TO 6
2 WRITE(6,20)
20 FORMAT(' RATIO OF CONDUCTIVITIES IS GREATER THAN 100')
STOP
3 IF(TCN.NE.0.0)GO TO 6
WRITE(6,30)
30 FORMAT(' THERMAL CONDUCTIVITY OF PIPE WALL IS ASSUMED TO BE LARGE'

```


TCL00037
TCL00038
TCL00039

1)
6 RETURN
END

PAGE 24

| | | | | | | | | | | | | | | | | |
|----------|------|---------|---------|----------|----------|-----------|---------|------|------|-------|-------|------|------|------|------|----------|
| 97. | 92. | 87. | 82. | 77. | 72. | 67. | 62. | 0006 | 0032 | .011 | .03 | .069 | .106 | .1 | 6802 | DATA0001 |
| 1000. | 50. | 50. | 50. | 15. | 15. | 45. | 45. | 30. | 30. | .0109 | .0109 | .75 | .75 | .158 | | DATA0002 |
| | .4 | .85 | .85 | .002675 | .002675 | -.0001125 | 7.5 | 150. | 150. | 4. | 4. | .5 | .5 | | | DATA0003 |
| | 1. | -.0049 | -.0049 | .10466E1 | .10466E1 | -.8807E-1 | .274E-2 | | | | | | | | | DATA0004 |
| .17664E2 | .750 | -.563E1 | -.563E1 | .0327 | .0327 | .375 | 0.0 | | | 0.0 | 50.3 | .414 | | | | DATA0005 |
| .46 | | .18 | .375 | .4 | .4 | .4 | .375 | | | 0.0 | 0.0 | | | | | DATA0006 |
| .030 | | | | | | | .5 | | | | | | | | | DATA0007 |
| | | | | | | | | | | | | | | | | DATA0008 |



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